Summary

2012 Propulsion Controls and Diagnostics (PCD) Workshop

High Speed Propulsion Modeling and Control

These presentations were made at the biannual NASA 2012 Propulsion Controls and Diagnostics (PCD) Workshop in Cleveland Ohio and they cover research work that has been done since the last workshop in the High Speed area of the Fundamental Aeronautics Program, that includes both supersonics and hypersonics propulsion.

Overview

AeroPropulsoServoElasticity
Fundamental Aeronautics – Supersonics Project

George Kopasakis

NASA Glenn Research Center
Cleveland, Ohio

Propulsion Control and Diagnostics (PCD) Workshop
Cleveland OH, Feb. 28 – March 1, 2012

Overview of APSE Propulsion Team/Task

- **Team: All NASA GRC** (2FTE's)
  George Kopasakis
  Joseph Connolly
  Nulie Theofilaktos
  Jeffrey Chen

- **NRAs**
  -- Past no NRA's
  -- New NRA Announcement this Spring

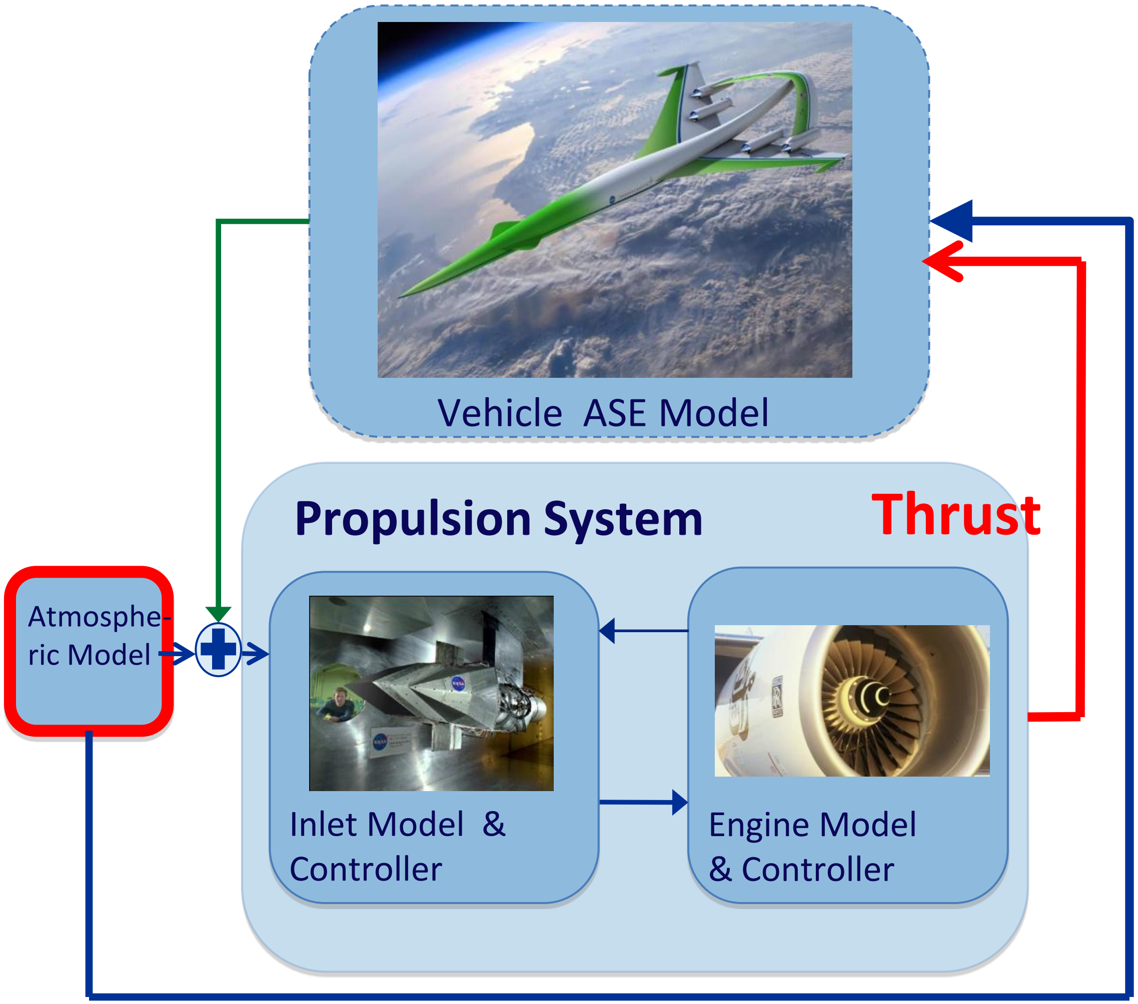
- **Type of Studies Conducted**
  -- So far Analytical Studies (TRL 1-3)

Project Challenges

- **The Supersonics Project aims to conduct fundamental research necessary to develop the technologies for supersonic transports**

- **As such the project identified several technical challenges**
  -- Among these challenges are also
  - **Performance challenges**, AeroServoElasticity (ASE) & Aero-Propulso-Servo-Elasticity (APSE) analysis and design
  - **Efficiency challenges**, including supersonic cruise efficiency

Objective
AeroPropulsoServoElasticity (APSE)



- Integrated Modeling &Controls Design
- Vehicle Stability
- Ride quality

- Cruise Efficiency

Design and Analysis

Integrated APSE Model
(NASA GRC in collaboration with NASA LaRC)

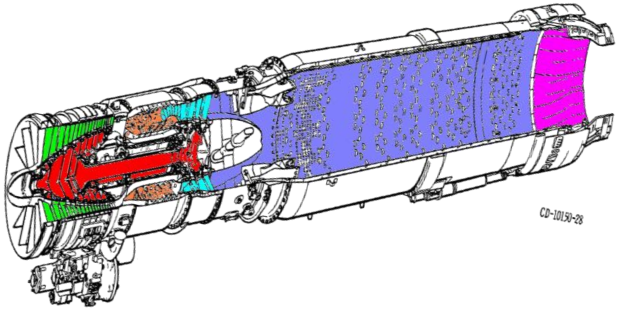
Approach - Propulsion Modeling

Engine

- Based on component gas lump volume dynamics and performance characteristics & separately stage-by-stage – reported in 2009 WorkShop (2009 WS)

  -- Developed Nonlinear and linear propulsion system models turbo jet (J85-13 engine) and turbofan – 2009 WS

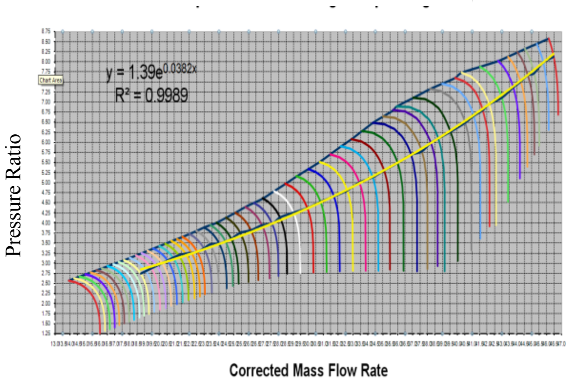
  -- Developed 1st version of N+3 variable cycle engine model



$$\frac{\partial}{\partial t}(\rho_s A) + \frac{\partial}{\partial x}(\rho_s A v) = 0$$

$$\frac{\partial}{\partial t}(\rho_s A v) + \frac{\partial}{\partial x}(\rho_s A v^2) = -Ag\frac{\partial P_s}{\partial x}$$

$$\frac{\partial}{\partial t}(\rho_s A u_t) + \frac{\partial}{\partial x}(\rho_s A v H) = 0$$



- Derived methodology for developing control schedules (J85-13)

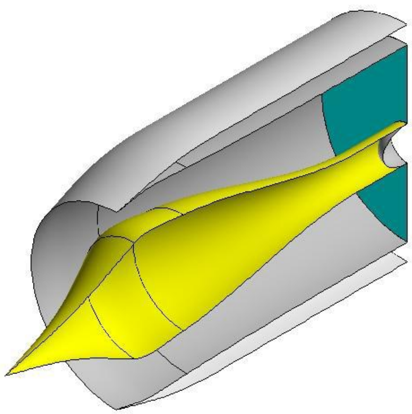
  -- For compressor operating line (2009 WS), and

  for exit nozzle area

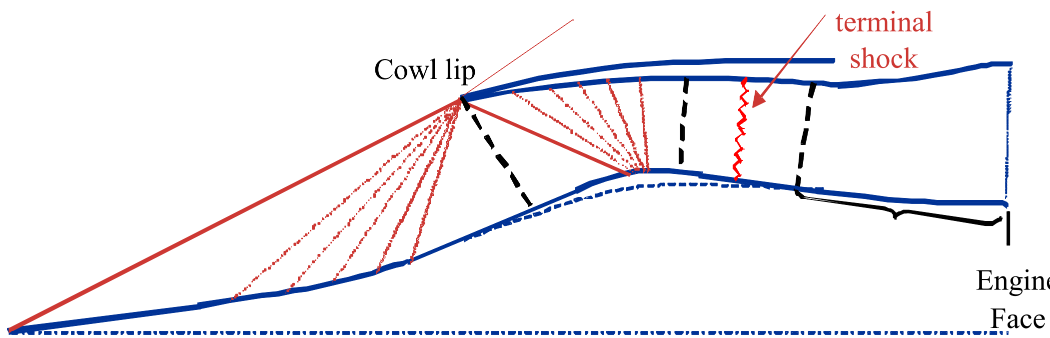
Approach- Propulsion Modeling

Inlets & Nozzles

- Initially developed linear mixed compression inlet models utilizing LAPIN (legacy Fortran code) – 2009 WS
- **Inlets** - Quasi 1-Dimensional (1D) Computational Fluid Dynamics (CFD) and Compressible flow w/ variable geometries

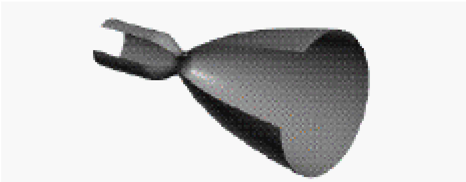


Axisymmetric External Compression inlet



Mixed Compression Inlet Diagram

- **Nozzles –** CFD based on MacCormack method

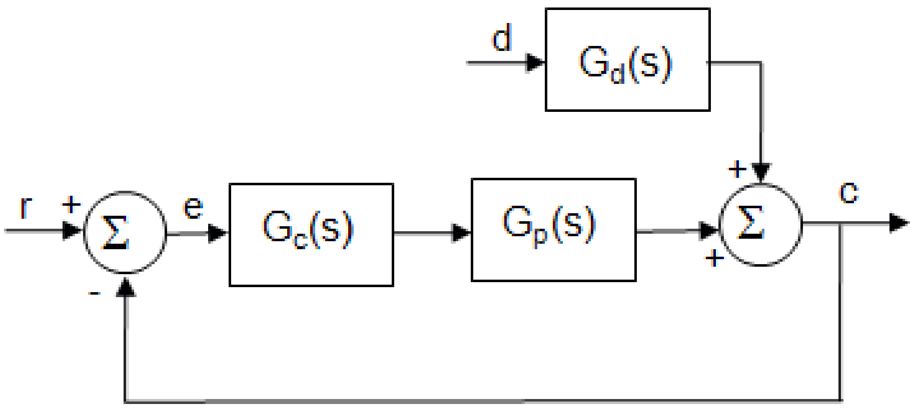


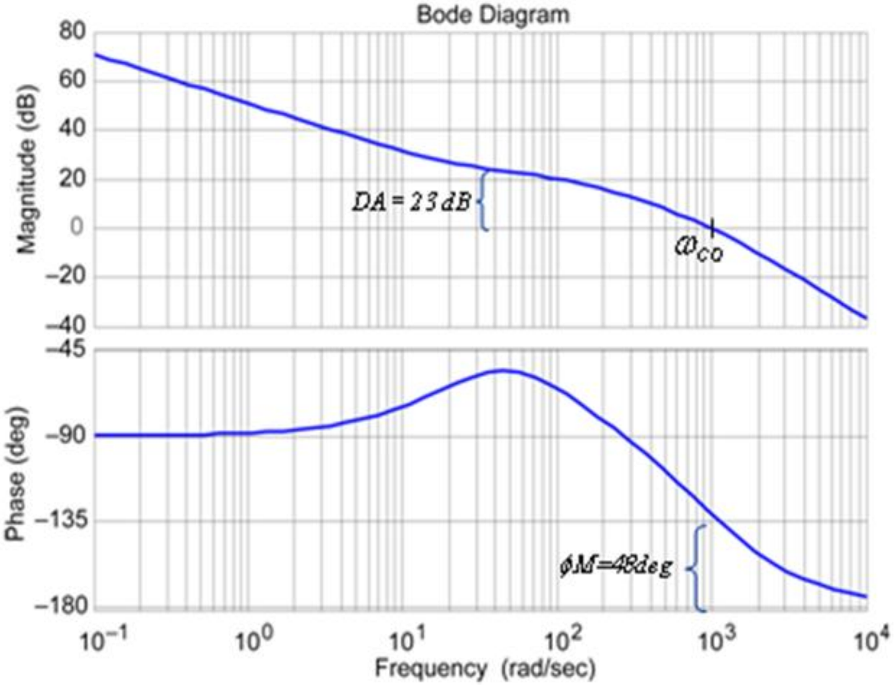
Convergent–Divergent (CD) Nozzle

Approach- Propulsion Controls

Feedback Controls Design – 2009 WS

- Based on feedback controls loop shaping design developed in this task
  -- Relates hardware performance to design requirements
  -- Maximizes control system performance



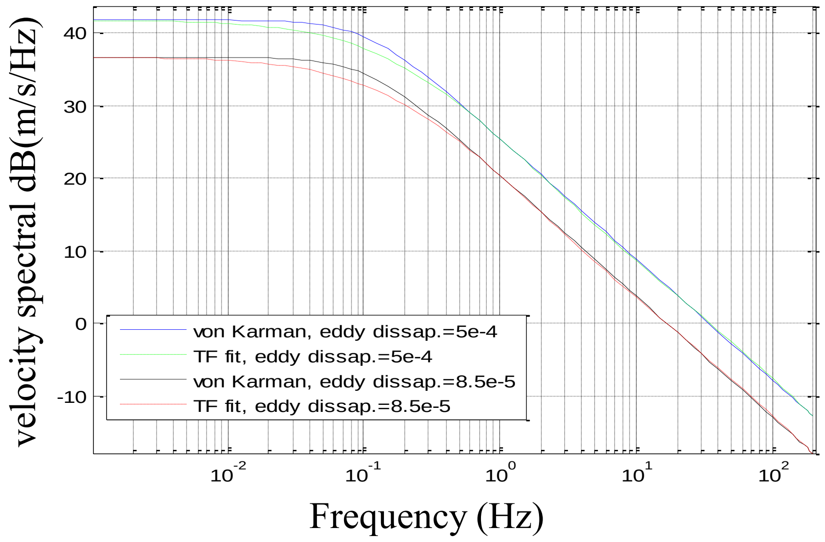


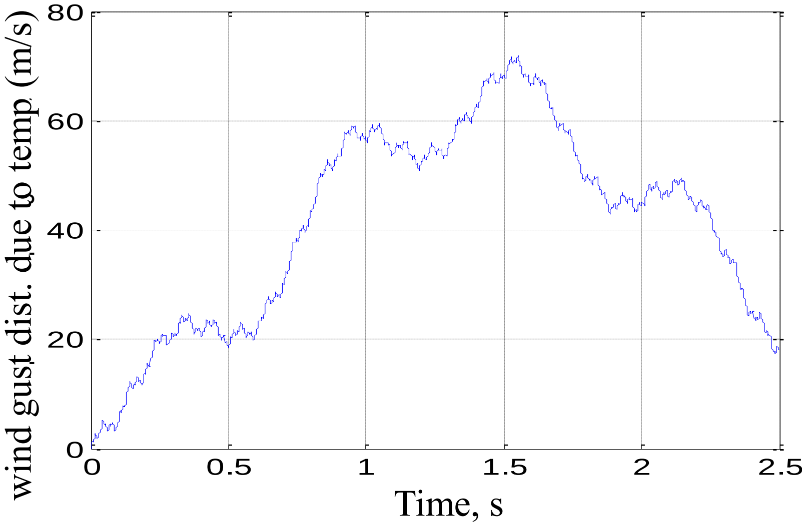
- Methodology used to design engine fuel actuation controls of linear and nonlinear propulsion system
- Also to design shock position controls for a supersonic inlet

Approach Propulsion Disturbance

Atmospheric Turbulence – 2009 WS

- Developed atmospheric turbulence models (wind gust, temp, pres)
  -- More accurate than existing models by ~ 7dB/decade
  -- Modeling fractional order nature of atmospheric turbulence



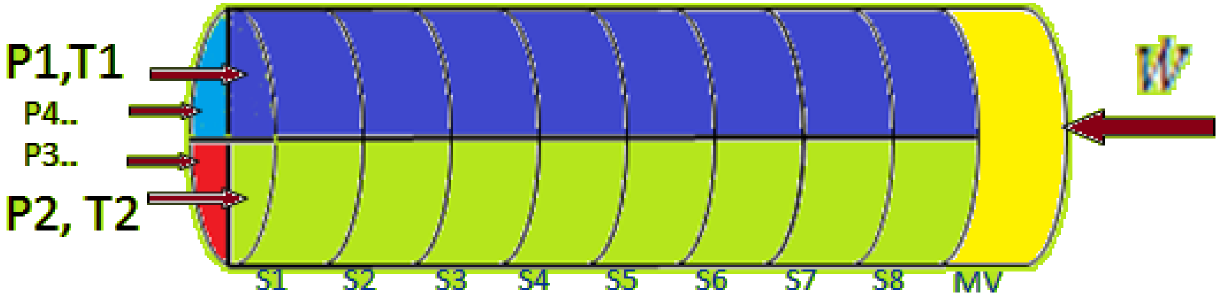


- Also need to develop disturbance models for AeroServoElastic, Pitch, Yaw and Roll

Approach Propulsion Modeling for Distortion And Boundary Layer Separation

Distortion

- By developing parallel flow path component models
  - -- Started with compressor utilizing stage-by-stage, 2D Euler in cylindrical coordinates
  - -- In the future extend to model fans and inlets



Parallel Flow Path Compressor Model

Boundary Layer

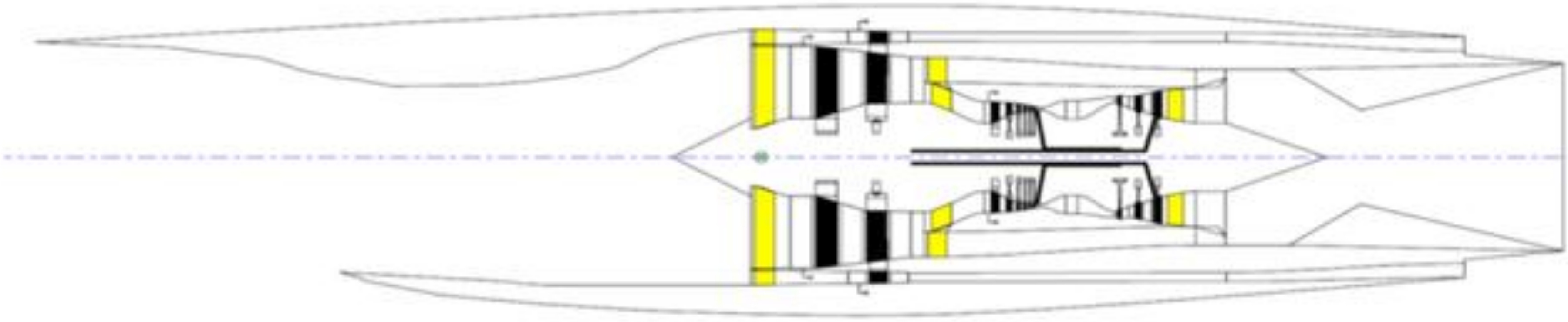
- May model by including effective area in the dynamics, else it would require more than 1D

Variable Cycle Propulsion System Studies

- Dual Spool variable cycle – High bypass at low altitudes to low bypass high altitudes

- Noise abatement for overland flight
  -- Through external bypass & through nozzle design

- Modeling approach same as with J85-13 approach except this engine has additional components and flow paths



Publications

1. Kopasakis - Feedback Control Systems Loop Shaping Approach with Practical Considerations, NASA/TM-2007-215007
2. Kopasakis et al. - Volume Dynamics Propulsion System Modeling for Supersonic Vehicles, GT2008-50524, NASA/TM-2008-215172
3. Connolly et al. - Turbofan Volume Dynamics Model for Investigation of Aero-Propulso-Servo-Elastic Effects in a Supersonic Commercial Transport, AIAA-2009-4802
4. Kopasakis et al. - Shock Positioning Controls Design for a Supersonic Inlet, AIAA-2009-5117
5. Kopasakis et al. - Volume Dynamics Propulsion System Modeling for Supersonic Vehicles, *Journal of Turbomachinery* (Vol. 132, October 2010)
6. Kopasakis - Atmospheric Turbulence Modeling for Aero Vehicles- Fractional Order Fits, NASA/TM-2010-216961
7. Kopasakis - Modeling of Atmospheric Turbulence as Disturbance for Control Design and Evaluation of High Speed Propulsion, GT2010-22851
8. Connolly et al. – Loop Shaping Control Design for a Supersonic Propulsion System Model Using QFT Specifications and Bounds” AIAA-2010-7068
9. Connolly et al. - Nonlinear Dynamic Modeling and Controls Development for Supersonic Propulsion System Research, AIAA 2011-5635.
10. Kopasakis - Modeling of Atmospheric Turbulence as Disturbance for Control Design and Evaluation of High Speed Propulsion, *Journal of Dynamic Systems* (vol. 134, issue 2, 2012).
11. Kopasakis et al. - Quasi 1D Modeling of Mixed Compression Supersonic Inlets, AIAA 2012-0775.
12. Kopasakis et al. - Quasi One-Dimensional Unsteady Modeling of External Compression Supersonic Inlets, AIAA, JPC, 2012 (pending).

Modeling of Concept Propulsion System

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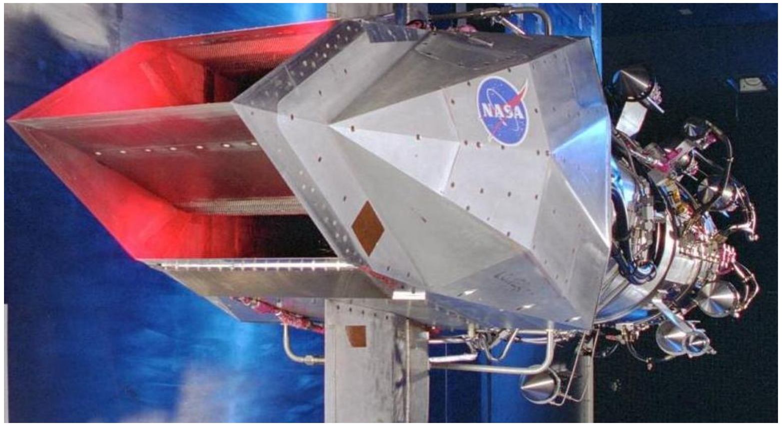
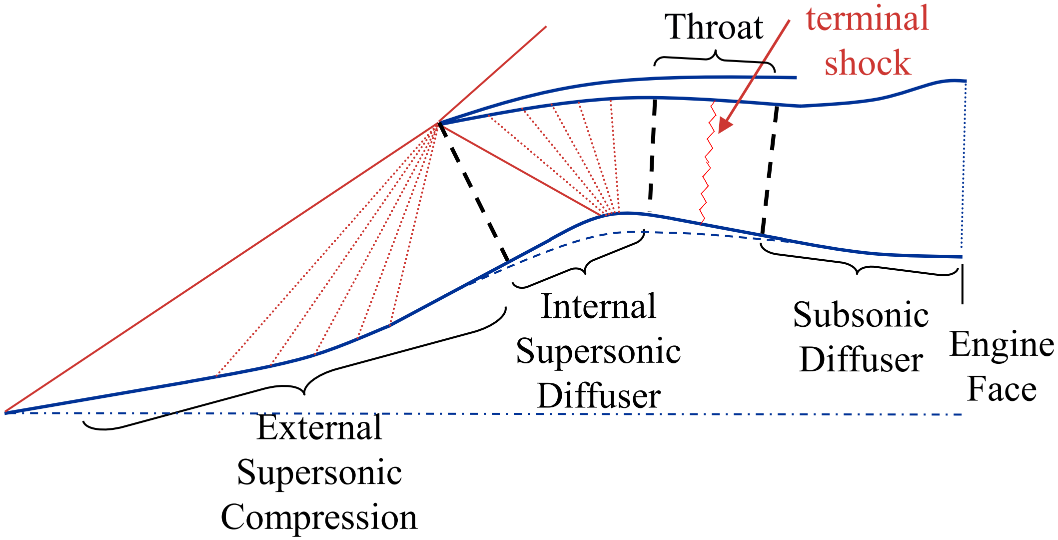
Outline

- **Supersonic Inlet modeling**
  - -- Mixed Compression Inlet
  - -- External Compression Inlet
- **Parallel Flow Path Modeling**
  - -- Parallel Compressor Modeling
- **Engine Control Schedules**
  - -- Compressor Schedule
  - -- Exit Nozzle Area Schedule
- **Nozzle Modeling**
- **Variable Cycle Engine (VCE) Modeling**
- **Concluding Remarks/Future**

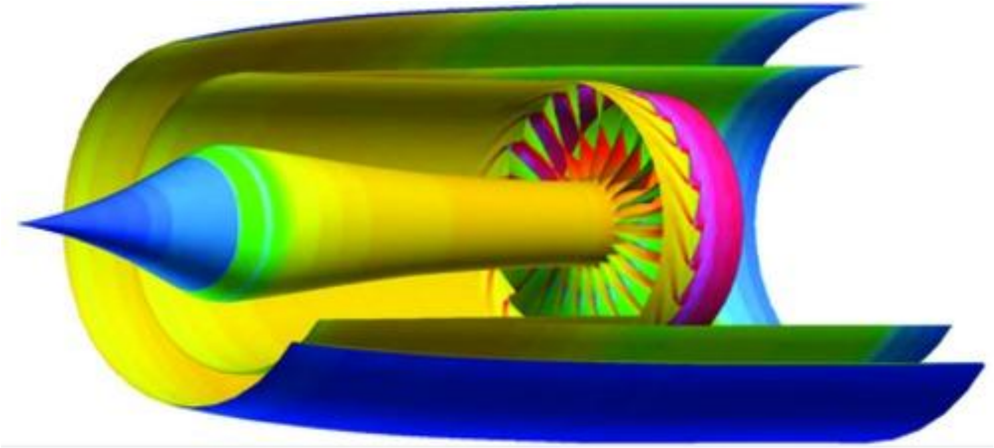
Supersonic Inlets Modeling

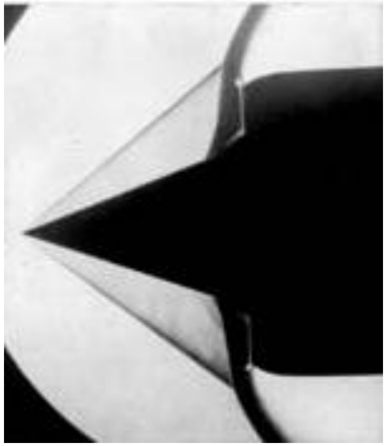
- Started with Mixed Compression Supersonic inlets





- Now focusing on external compression axisymmetric Inlets
  -- Better overall performance for Mach 1.8 or less





External Compression Modeling

- Isentropic compressible flow relations to model a system of oblique shocks (no dynamics assuming external dynamics are significantly faster than internal)

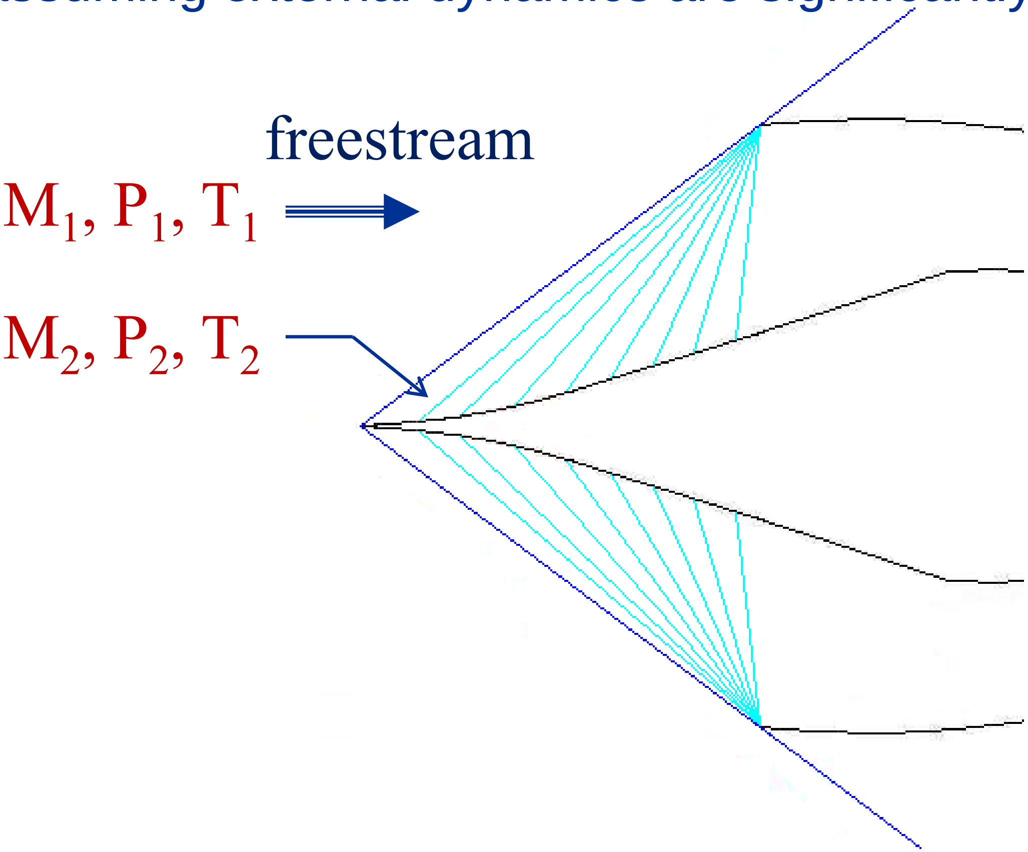
$$\tan\theta = 2\cot\beta \frac{M_{1N}^2 - 1}{M_1^2(\gamma + \cos 2\beta) + 2}$$

$$M_{1N} = M_1 \sin\beta$$

$$\frac{P_2}{P_1} = 1 + \frac{2\gamma}{\gamma+1}\left(M_{1N}^2 - 1\right)$$

$$\frac{T_2}{T_1} = \frac{P_2}{P_1}\frac{(\gamma-1)M_{1N}^2 - 2}{(\gamma+1)M_{1N}^2}$$

$$M_2 = \frac{1}{\sin(\beta-\theta)}\sqrt{\frac{1+\frac{\gamma-1}{2}M_{1N}^2}{\gamma M_{1N}^2 - \frac{\gamma-1}{2}}}$$



- Sufficient discretization of centerbody angle (Δθ) when cowl lip conditions are not changing
- Shocks focusing at the cowl lip also verifies inlet geometry for designed condition

Internal Compression Modeling

Supersonic & Subsonic Diffusers

– Internal supersonic and subsonic compression – Quasi 1D CFD based on compressible Euler

Continuity of Mass

$$\frac{\partial \rho_s}{\partial t} = -\frac{1}{A}\frac{\partial(\rho_s A v)}{\partial x} - \frac{\rho_s}{A}\frac{\partial A}{\partial t}$$

Momentum

$$\frac{\partial}{\partial t}(\rho_s v) = -\frac{1}{A}\frac{\partial}{\partial x}[(P_s + \rho_s v^2)A] + \frac{1}{A}\left(P_s\frac{\partial A}{\partial x} - \rho_s v\frac{\partial A}{\partial t}\right)$$

Energy

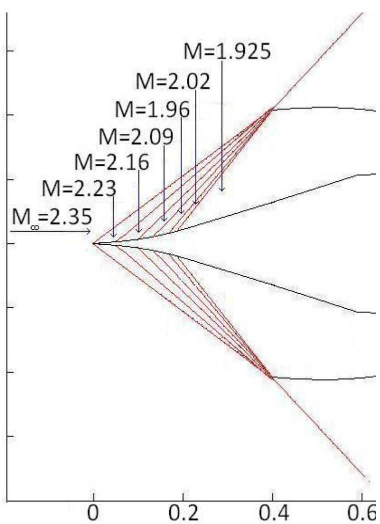
$$\frac{\partial}{\partial t}\left[\left(\frac{P_s}{\gamma - 1} + \frac{\rho_s v^2}{2}\right)\right] = -\frac{1}{A}\frac{\partial}{\partial x}\left[A\left(\frac{\gamma P_s v}{\gamma - 1} + \frac{\rho_s v^3}{2}\right)\right] - \frac{1}{A}\left(\frac{\gamma P_s}{\gamma - 1} + \frac{\rho_s v^2}{2}\right)\frac{\partial A}{\partial t}$$

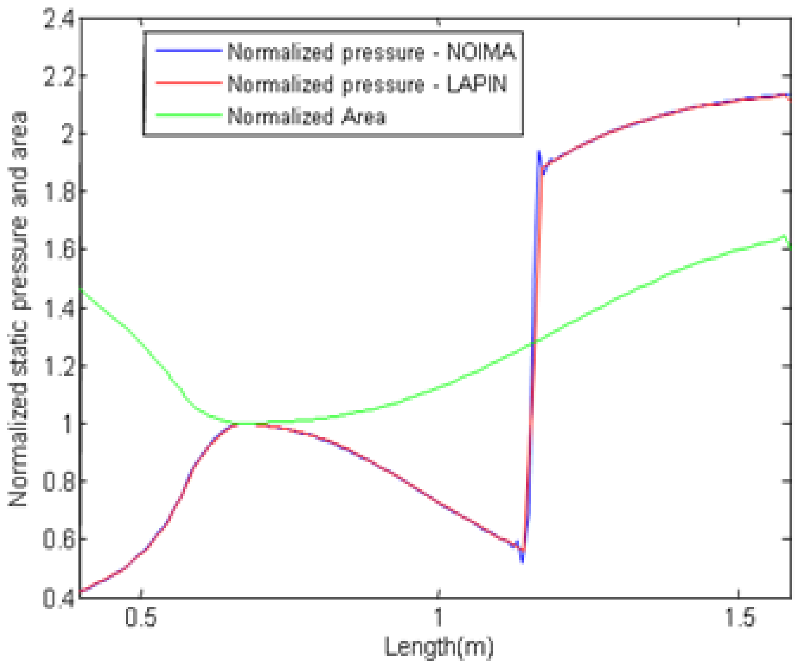
Overall CFD Equation

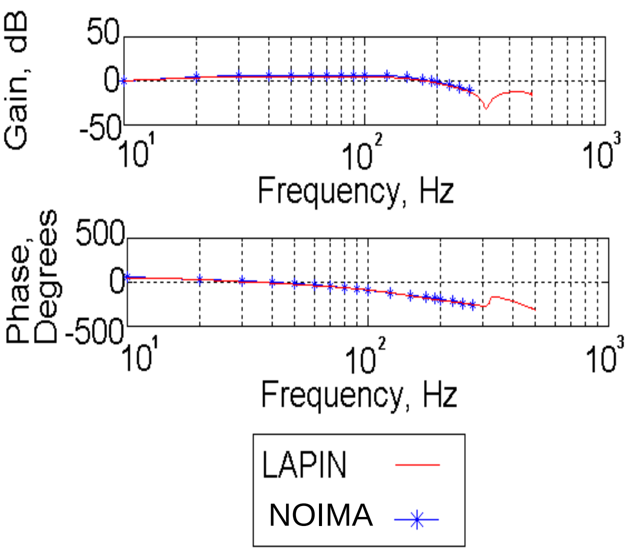
$$\frac{\partial}{\partial t}(W_{j,n}) = -\left(\frac{A_{n+1}F_{j,n+1} - A_{n-1}F_{j,n-1}}{2\Delta x A_n}\right) + \frac{S_{j,n}}{A_n}$$
$$+ S_v\left[\frac{\left(|v_n| + a_n\right)\left(A_{n+1}W_{j,n+1} - A_n W_{j,n}\right) - \left(|v_{n-1}| + a_{n-1}\right)\left(A_n W_{j,n} - A_{n-1}W_{j,n-1}\right)}{\Delta x A_n}\right]$$

Mixed Compression Inlets Modeling - Results

- New model (NOIMA) verified against legacy code named LAPIN, which was verified with testing
  - -- LAPIN written in FORTRAN (~ 80 routines), based on method of characteristics







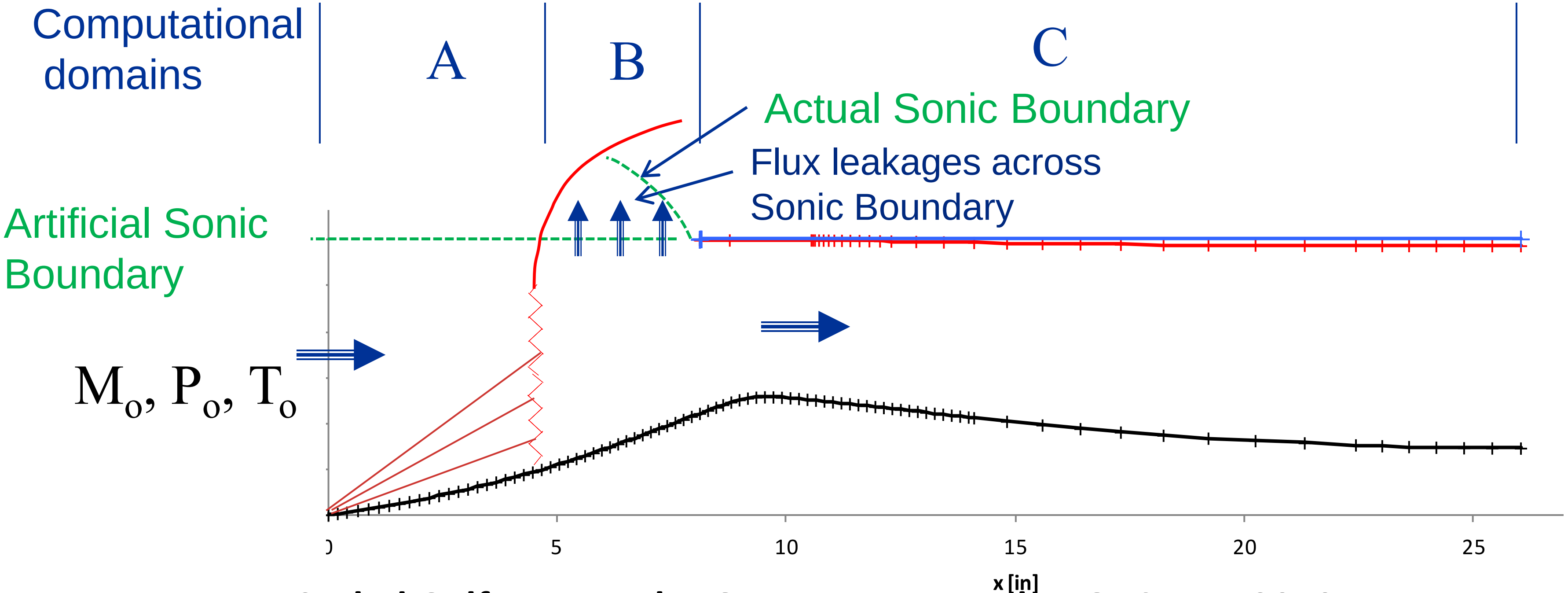
- New model can be used for controls design to increase performance and for propulsion and APSE integration

External Compression Inlet Modeling - Approach

Computational Domain

A. 1-D compressible flow cells w/ dynamics and averaging flows at shock boundary
B. Quasi 1-D CFD compressible flow cells w/ leakage fluxes estimation
C. Quasi 1-D CFD compressible flow cells

A-B. Moving computational domains



Scaled Gulfstream Inlet Geometry - tested at GRC Dec. 2010

External Compression Inlet Modeling – Challenges

Challenges

– Developing generalized formulations for conservation flux leakages across sonic boundary – Method hasn't worked yet

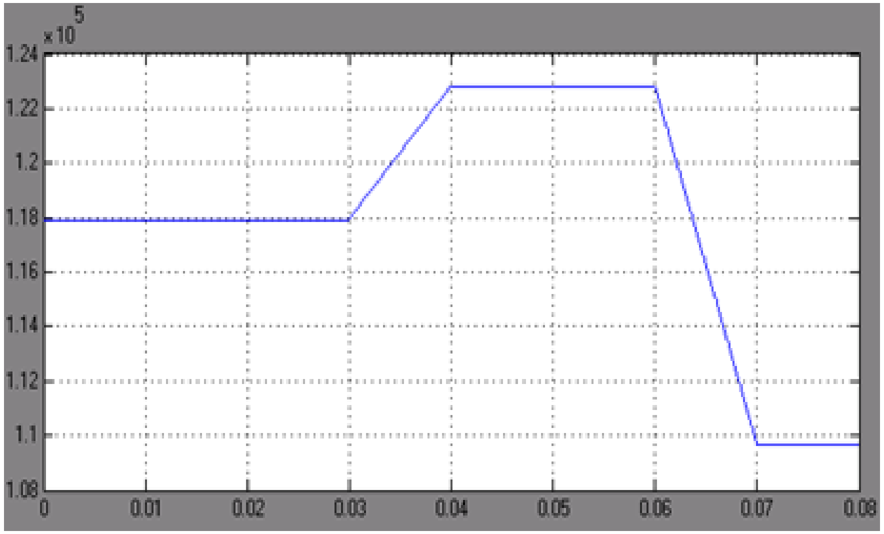
– Sensing the shock position to switch between compressible flow cells and quasi 1D CFD cells – Moving Domain

– Determined mass flow leakage based on test data for various engine face back pressures to calculate leakage fluxes – Approach worked but is not generalized

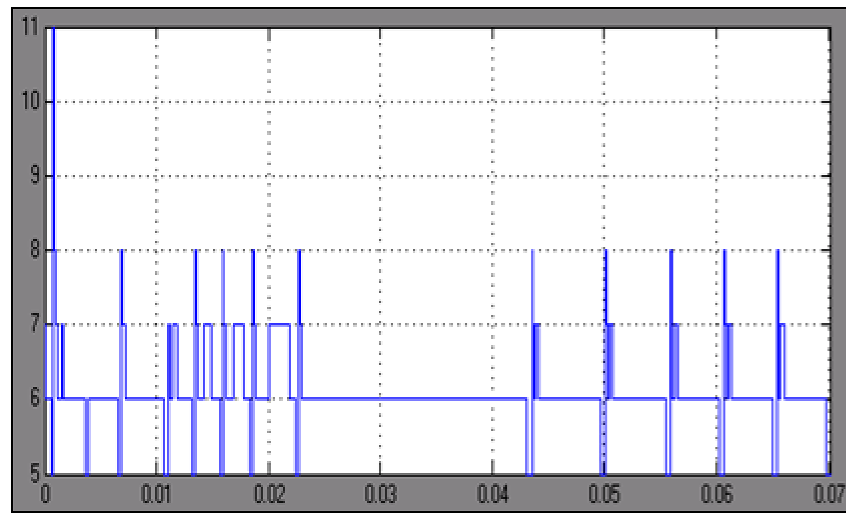
– Remaining issue for inlet dynamics Conical compressible flow field inherently 2D and 3D for pitch variations

Results – Ramping the Back Pressure

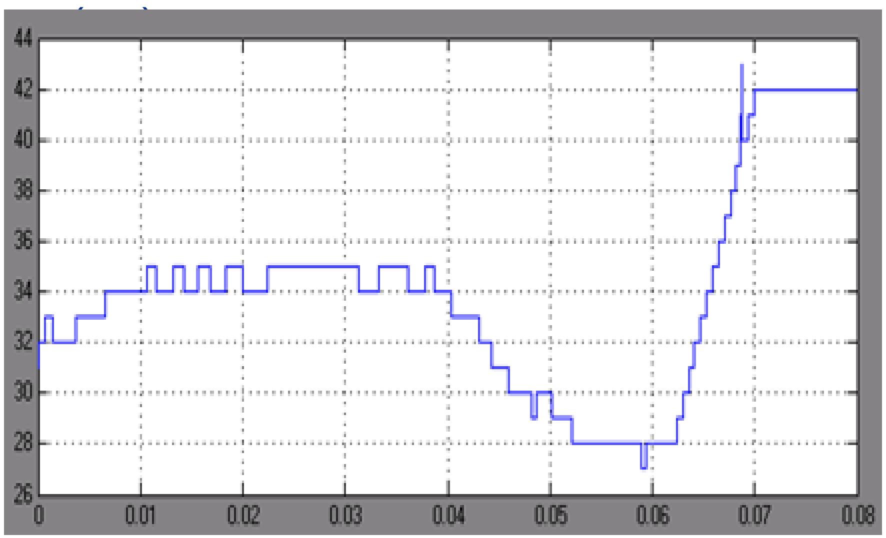
Back Pressure (N/m^2) vs. Time (sec)



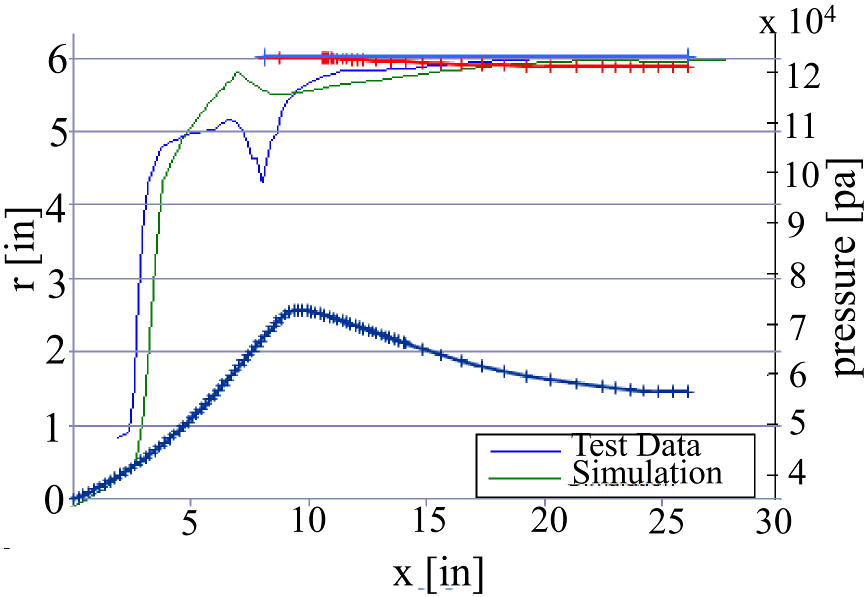
Shock Thickness (Cell) vs. Time (sec)



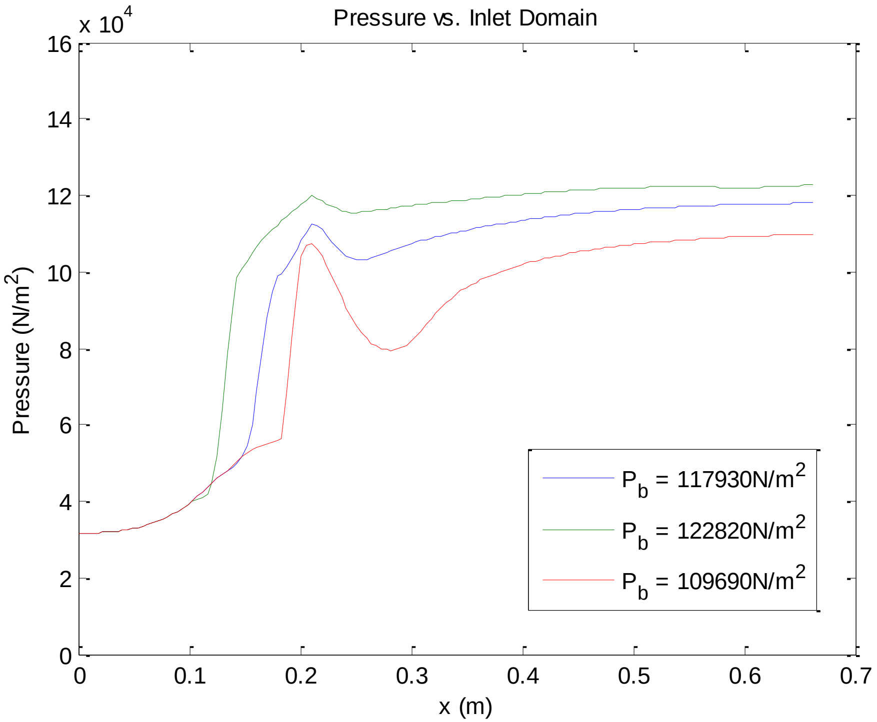
Upstream Shock Position (cell #) vs. Time



External Compression Inlet Results



Comparing test and Simulation Results



Pressure profile by ramping back pressure

Difference In Shock Position

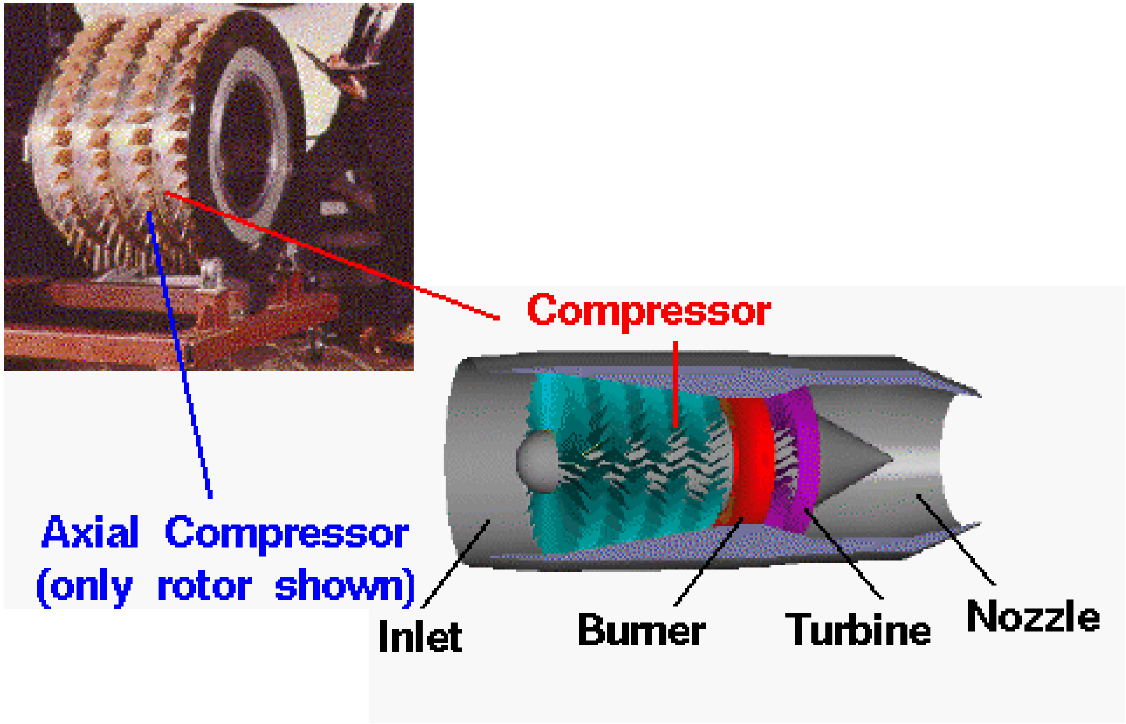
Back Pressure (N/m^2)	Test Data Shock Position (Cell)	Simulation Shock Position (Cell)
109690	41	42
117930	32	34-35
122820	26	28

Parallel Compressor Modeling

Objective

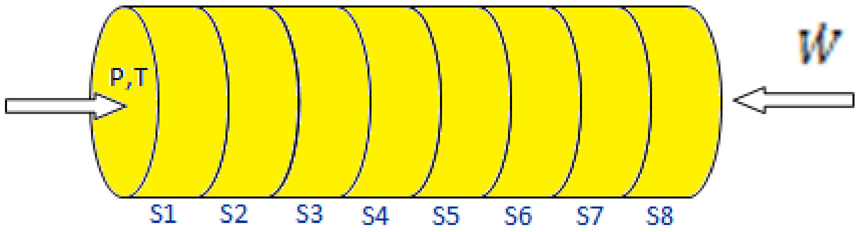
– Develop parallel flow path models of propulsion components to study effect of distortion on propulsion system dynamics and APSE

– First step in the process: develop compressor model with parallel flow paths

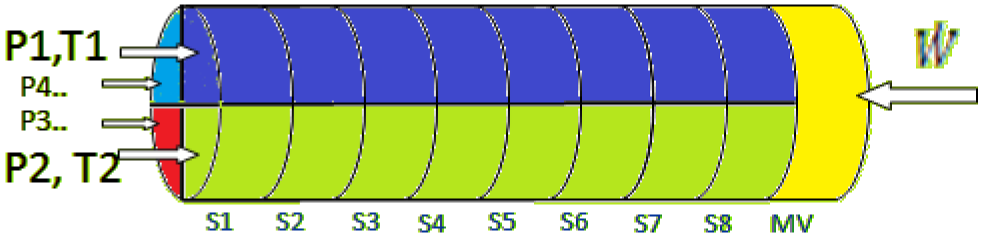


Overview

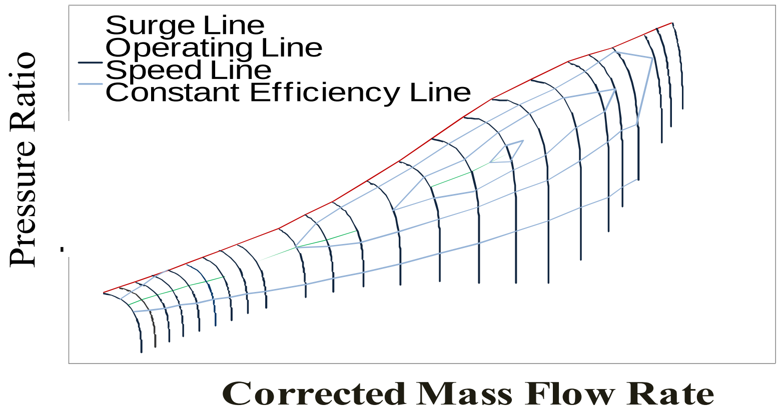
- New model derived in cylindrical coordinates - Euler
- Allows modeling of disturbance from changing flight conditions (pitch, yaw, roll, etc)
- Inlet conditions of Pressure, Temperature & outlet conditions of mass flow rate
- Path ratio of β_i - adjusting mass flow rate of stage maps by path ratio



Original model
Stage-by-stage, single flow path



New Model - Multiple Interacting Flow Paths



Parallel Compressor Modeling Approach

Conservation Dynamics in 2D Cylindrical Coordinates

- Equations were derived in cylindrical coordinates for compressible & inviscid flow, assuming flow properties do not vary in the radial direction

Conservation Equations $$\frac{\partial}{\partial t}(W_j) = -a_{xj}\frac{\partial}{\partial x}(F_{xj}) - a_{\varphi j}\frac{\partial}{\partial \varphi}(F_{\varphi j}) + S_j$$

j	Wj	Fxj	Fϕj	Sj	a_{xj}	$a_{\phi j}$
1	ρ_s	$\rho_s u$	$\rho_s w$	0	1	$\frac{1}{r}$
2	$\rho_s u$	$\rho_s u$	$\rho_s u$	$-\frac{\partial P_s}{\partial x}$	u	$\frac{w}{r}$
3	$\rho_s w$	$\rho_s w$	$\rho_s w$	$-\frac{1}{r}\frac{\partial P_s}{\partial \varphi}$	u	$\frac{w}{r}$
4	$\frac{P_s}{\gamma-1}+\frac{\rho_s V^2}{2}$	$\frac{\gamma P_s u}{\gamma-1}+\frac{\rho_s u^3}{2}$	$\frac{\gamma P_s w}{\gamma-1}+\frac{\rho_s w^3}{2}$	0	1	$\frac{1}{r}$

$$\frac{\partial}{\partial t}(W_{j,n,m}) = -a_{xj,n,m}\left(\frac{F_{xj,n+1,m} - F_{xj,n,m}}{\Delta x}\right) - a_{\varphi j,n,m}\left(\frac{F_{\varphi j,n,m+1} - F_{\varphi j,n,m-1}}{2\Delta\varphi}\right) + \frac{S_{j,n,m-1} - S_{j,n,m+1}}{2s}$$

Parallel Compressor Modeling Approach

Mixing volume - weighted average of pressure, temperature outputs from compressor stages

Mixing Volume Equations

Momentum:

$$\frac{\partial}{\partial t}\dot{W}_{mv} = \frac{A_{mv}g}{l_{mv}}\left[\sum_{j=1}^{m}\left(\beta_j P_{tj,i=n}\right) - P_{t,mv}\right]\left(1 + \frac{\gamma_{cp}-1}{2}M_{mv}^2\right)^{-\frac{\gamma_{cp}}{\gamma_{cp}-1}}$$

Continuity:

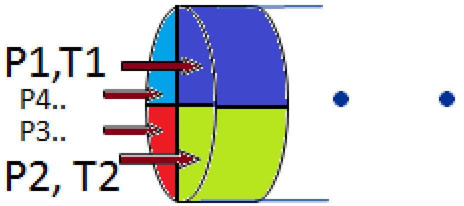
$$\frac{\partial}{\partial t}\rho_{s,mv} = \frac{1}{V_{mv}}\left(\dot{W}_{mv} - \dot{W}_{cb}\right)$$

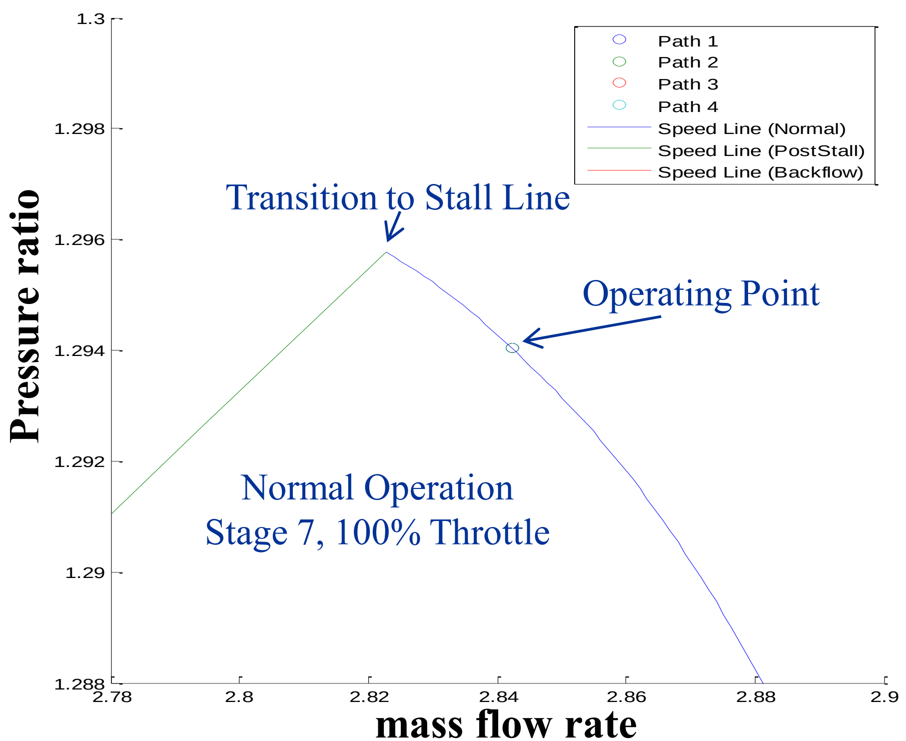
Energy:

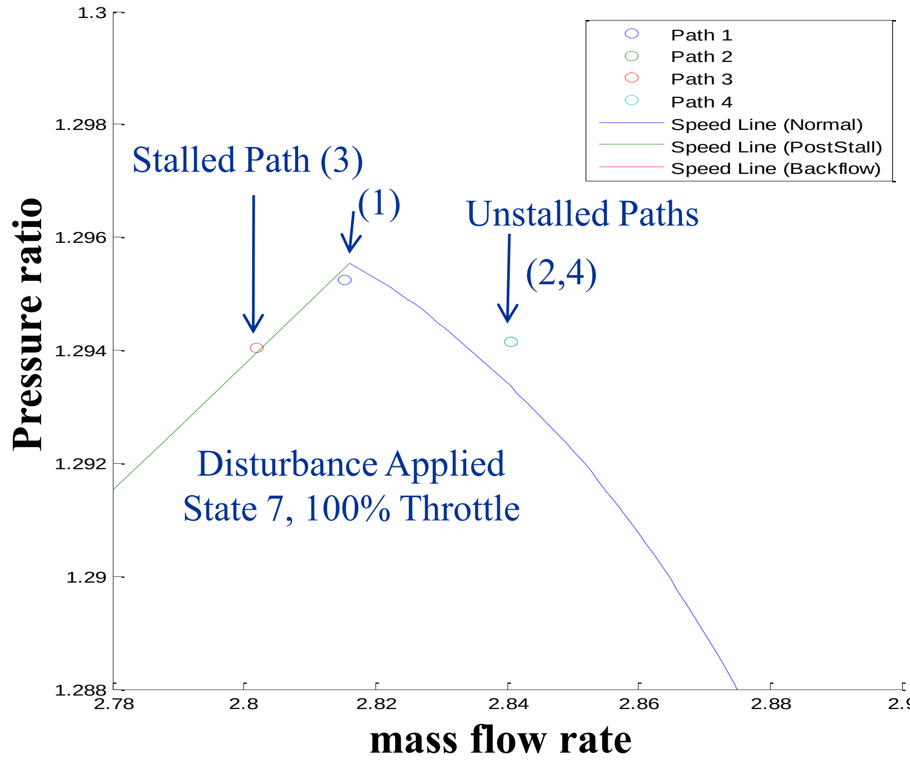
$$\frac{\partial}{\partial t}\rho_{s,mv}T_{t,mv} = \frac{\gamma_{mv}}{V_{mv}}\left[\dot{W}_{mv}\sum_{j=1}^{m}\left(\beta_j^2 T_{tj,i=n}\right) - \dot{W}_{cb}T_{t,mv}\right]$$

Parallel Compressor Modeling Results

- Pressure distortion of approximately 0.1% applied to path 1



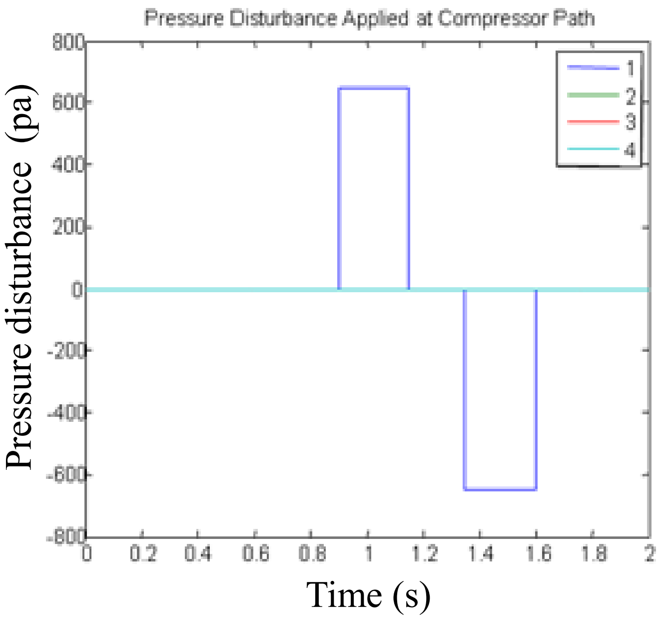


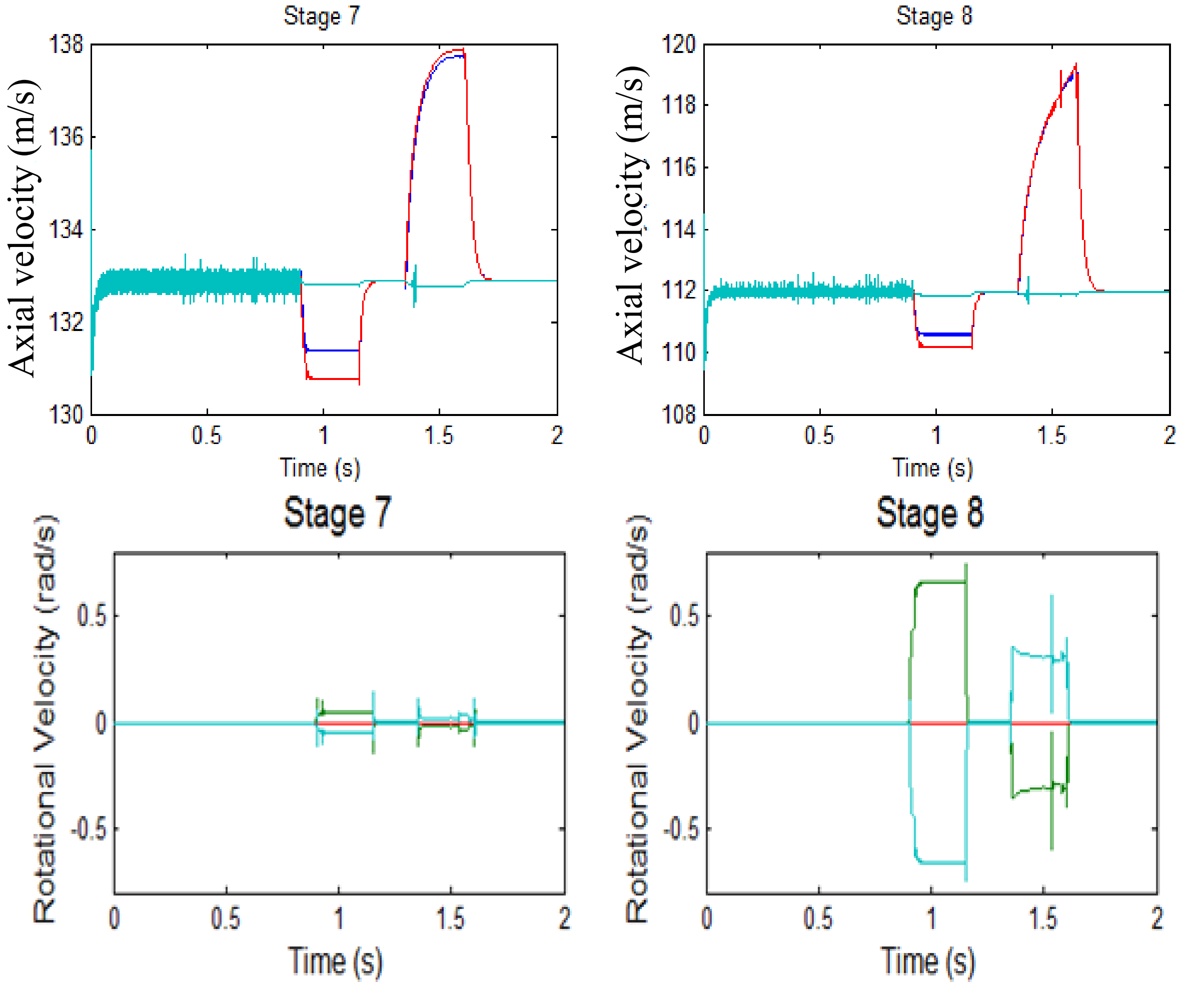


- Pressure disturbance moves Path 1, Path 3 operating points to surge line
- Would experience cascading stall if mass flow rate was not held constant (as with engine)

Parallel Compressor Modeling Results

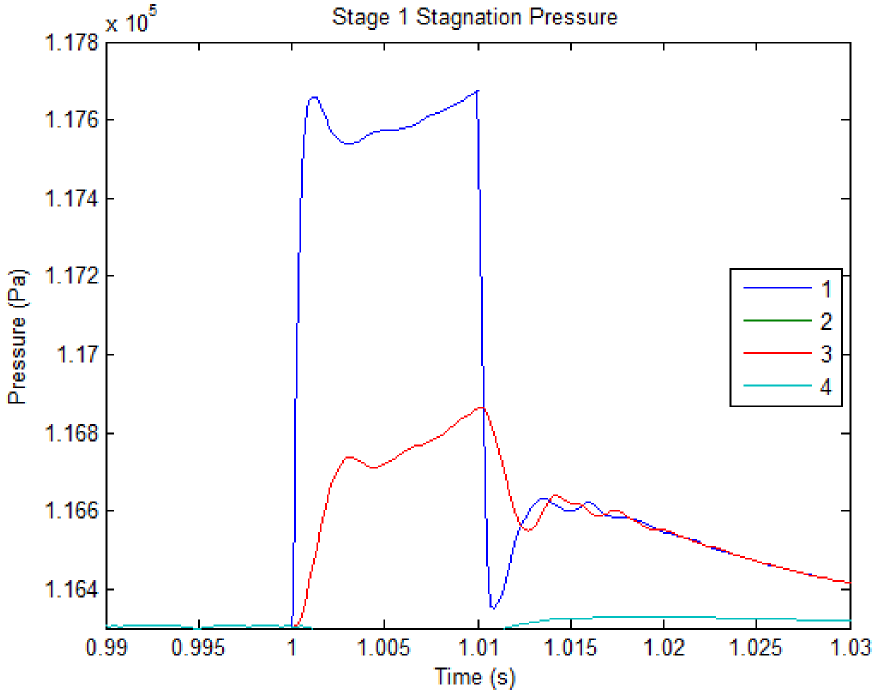
- Square wave distortion applied to compressor input, path 1

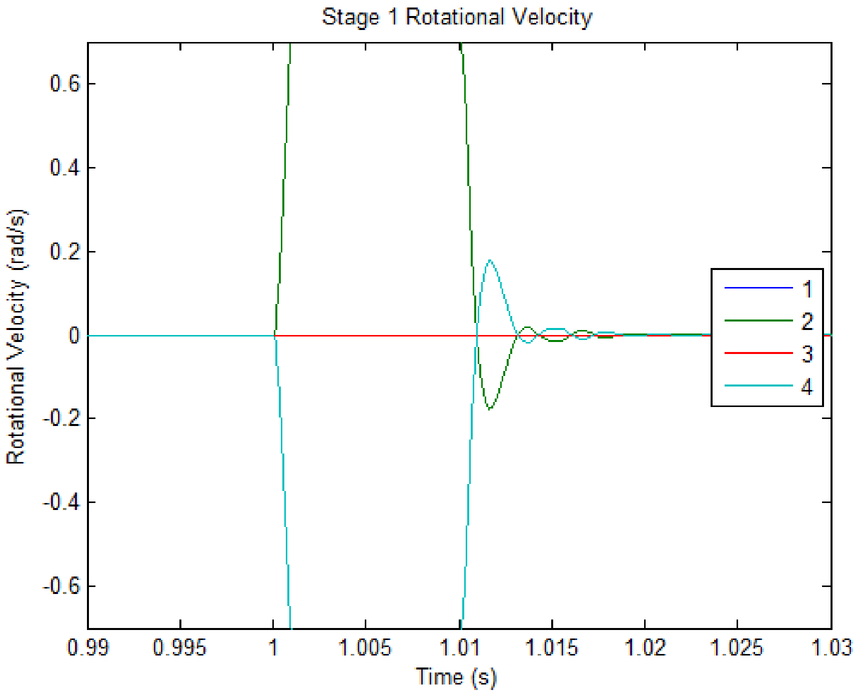




- Pulsating effect of rotational velocity from one stage to the next

Parallel Compressor Modeling Results

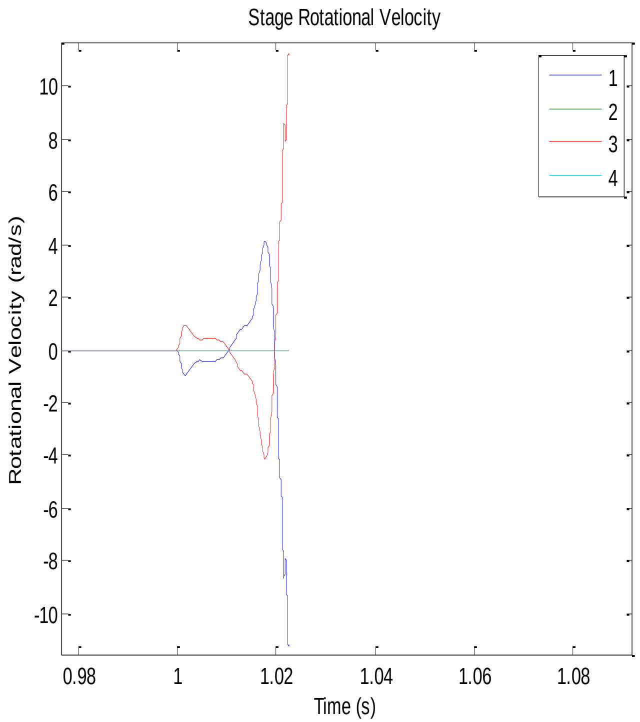


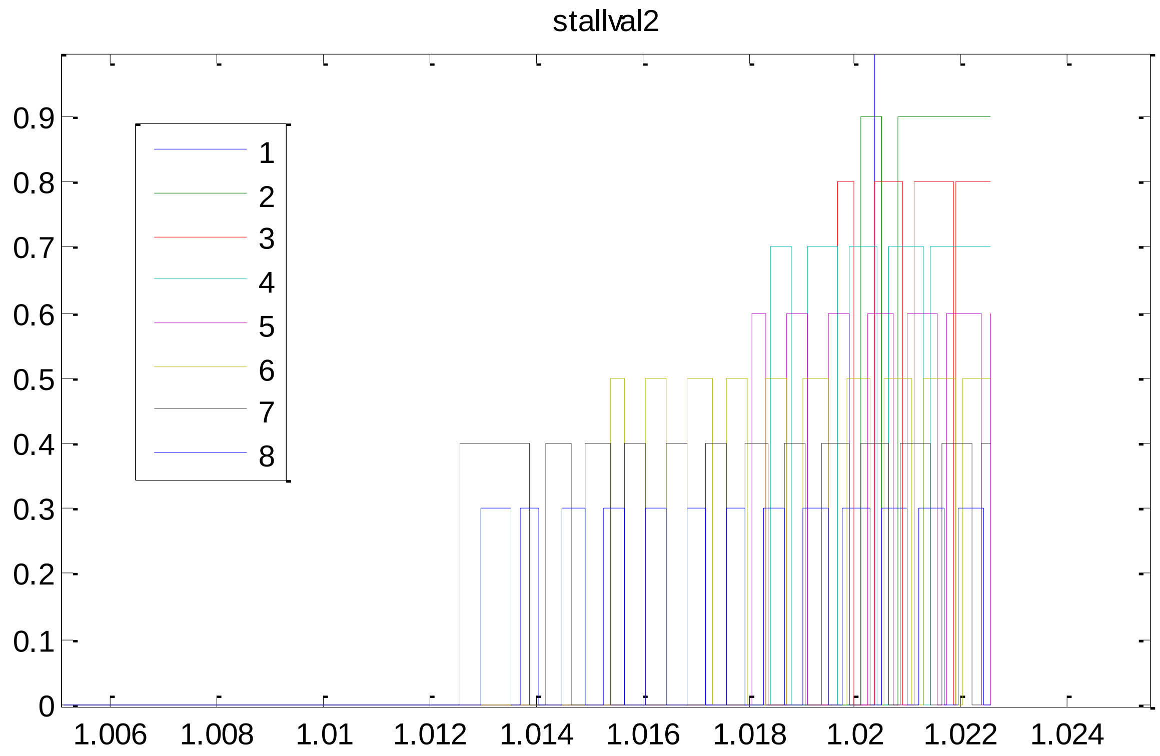


- Distortion with shorter duration applied (larger amplitude about 0.2%)
- Different disturbance frequencies produce different distortion patterns (different frequency domain response)

Parallel Compressor Modeling Results

1st Stage at 100% Speed w/ 1300pa (0.16%) Distortion on Sector 2 & 4



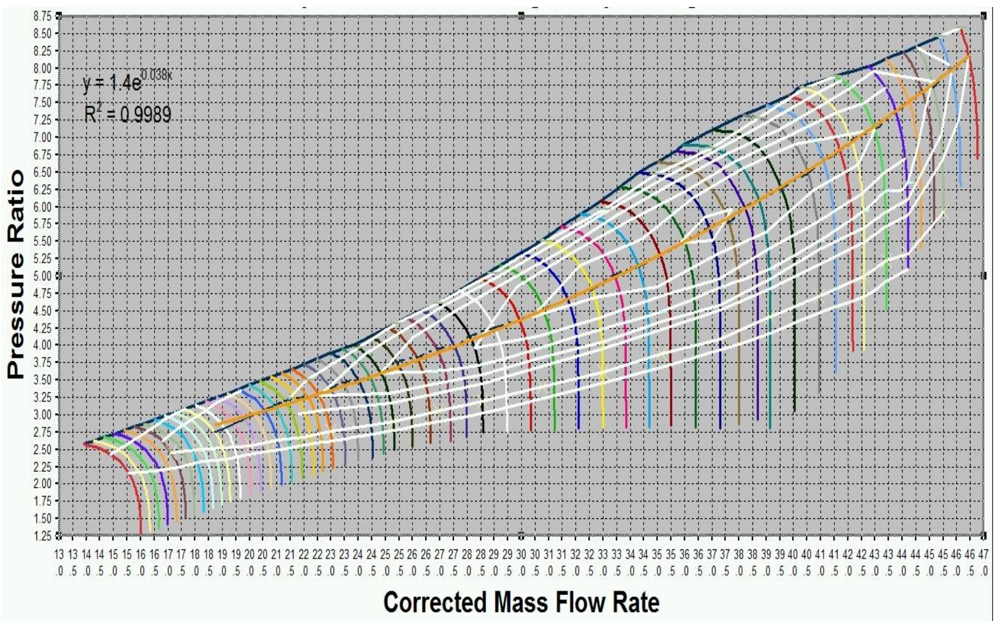


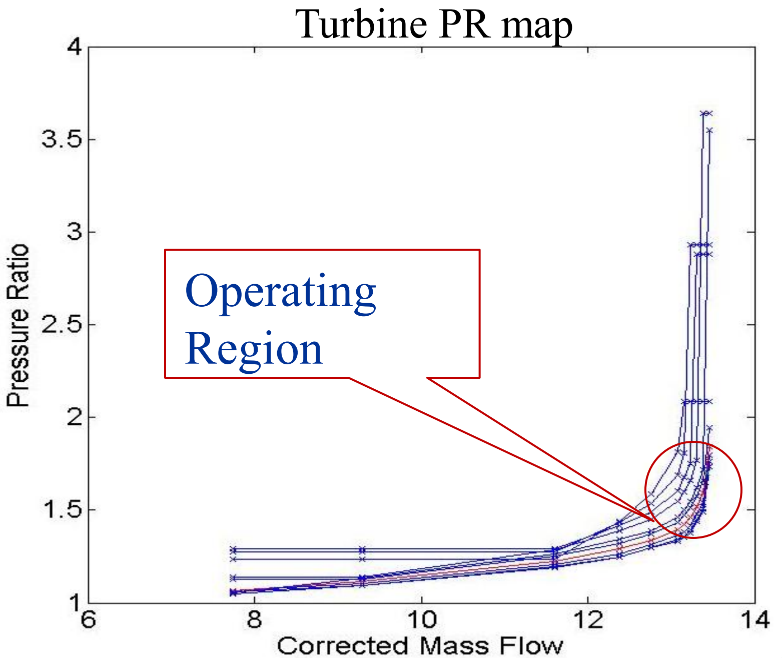
Stall Pattern – From Back to Front of Compressor

(0 Normal, > 0 Stall)

Engine Operating Schedules

- Prior (2009 WS) compressor operating schedule derivation approach developed for full speed envelope operation – used generic maps
  - -- Developed a bleed schedule – Info on Inlet Guide Vane (IGV) not available
  - -- First derived schedule utilizing isolated compressor model
  - -- Integrated w/ engine: could not maintain original operating line & turbine unchoked – compressor/turbine performance not exactly matched.
  - -- Corrected by rescaling turbine maps





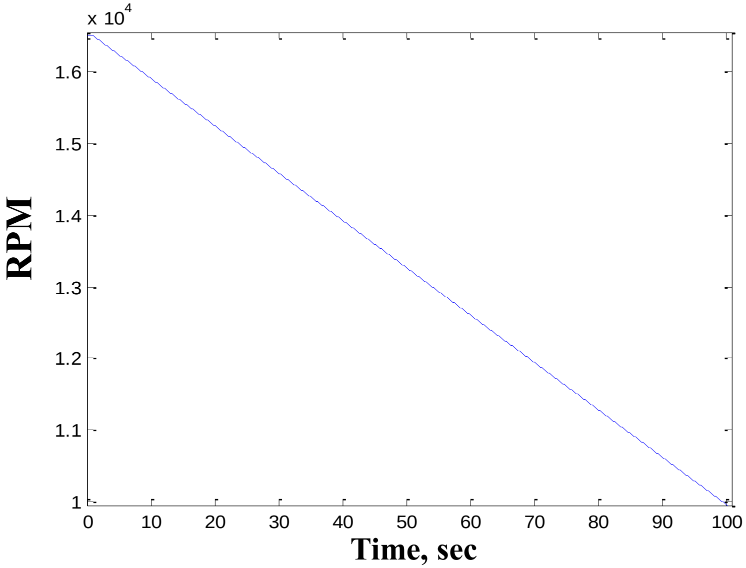
Exit Nozzle Area Schedule

- Developed exit nozzle area schedule approach – Objective to fully expand flow at nozzle exit

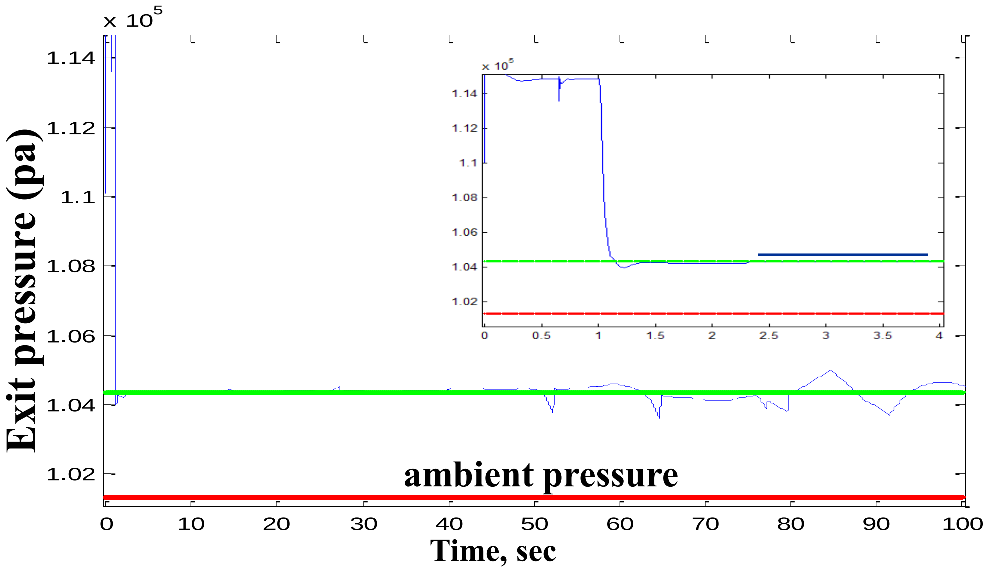
  -- Approach based on PR vs. Cd (flow discharge coefficient) schedule & area limit vs. speed

  -- Creates feedback system w/ instabilities – Designed Notch filters to stabilize system

  -- System sensitive to unmatched compressor/turbine – required rescaling



Engine Speed (100% to 60%)



Exit Nozzle Pressure as Speed Decreases Starting from 100%

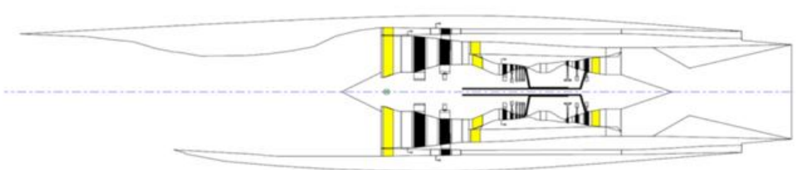
Nozzle Modeling

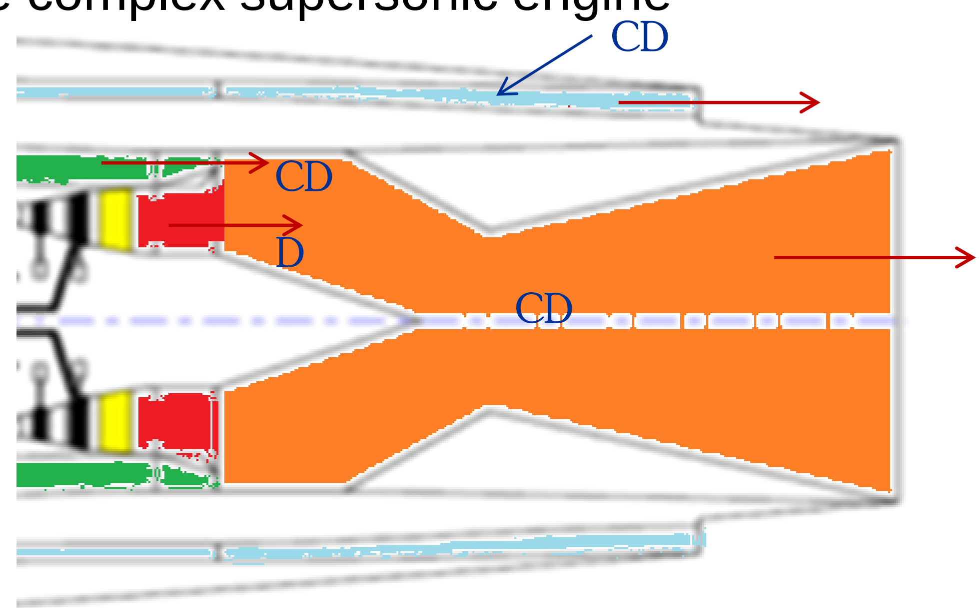
Objective/Approach

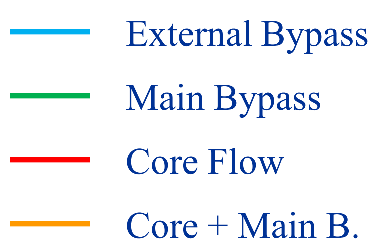
- Develop 1D CFD model for exit nozzles for thrust dynamics (before used nozzle lump volume and chocked compressible flow function)
  -- Chosen method: MacCormack's predictor-corrector technique assuming subsonic-supersonic isentropic nozzle flow

- **Step one** - develop model for generic Convergent-Divergent (CD) nozzle geometry

- **Step two** – develop model for more complex supersonic engine-nozzle concept geometry



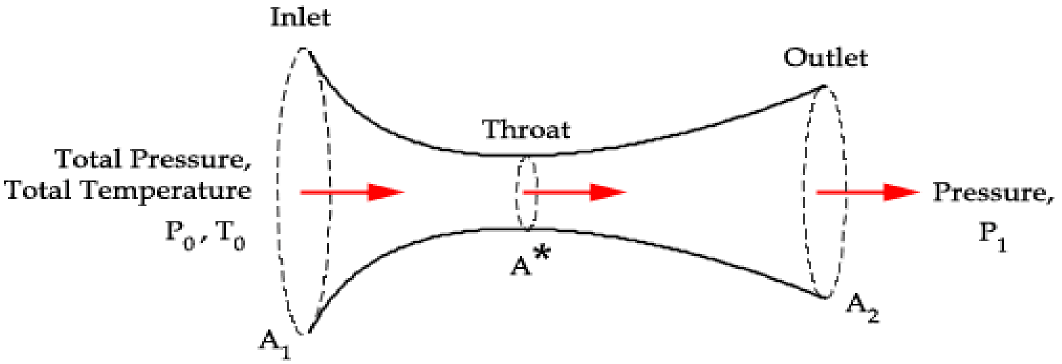


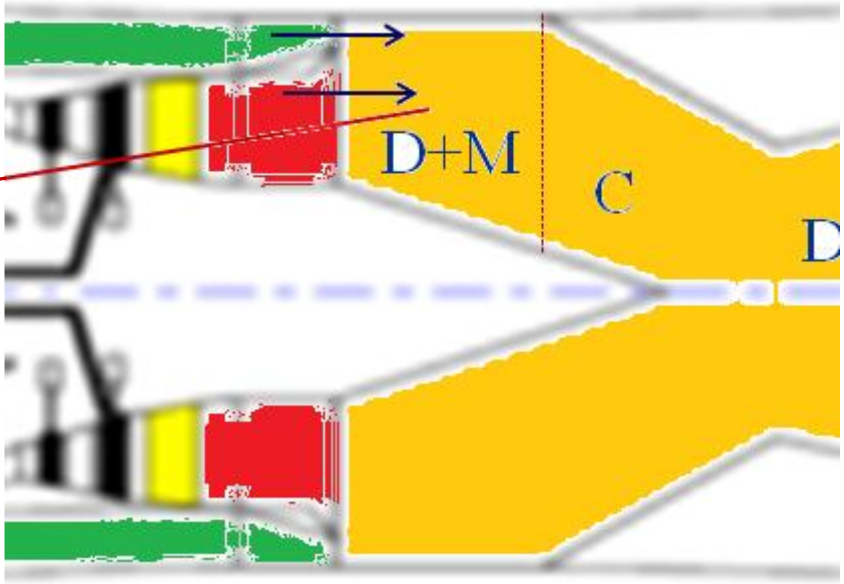


Nozzle Modeling

Converging-Diverging Nozzle

- Throat and Exit Areas used from N+3 engine simulation
- Used simple shape profile – actual N+3 nozzle profile not known
- Implemented MacCormack's method - variable area to be implemented in formulations
- Some 2D may need to be done
- For propulsion system exit nozzle area schedules need to be developed





CFD Method- Predictor Step

Predictor

$$\left(\frac{\partial\rho}{\partial t}\right)_i^t = -\frac{1}{A}\rho_i^t u_i^t\left(\frac{A_{i+1}-A_i}{\Delta x}\right) - u_i^t\left(\frac{\rho_{i+1}-\rho_i}{\Delta x}\right) - \rho_i^t\left(\frac{u_{i+1}-u_i}{\Delta x}\right)$$

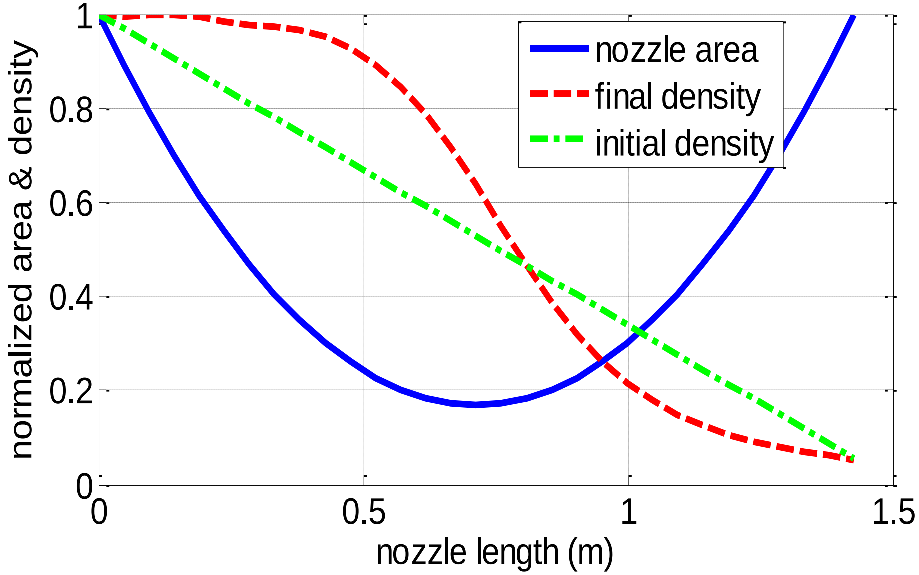
$$\bar{\rho}_i^{t+\Delta t} = \rho_i^t + \left(\frac{\partial\rho}{\partial t}\right)_i^t \Delta t$$

Corrector

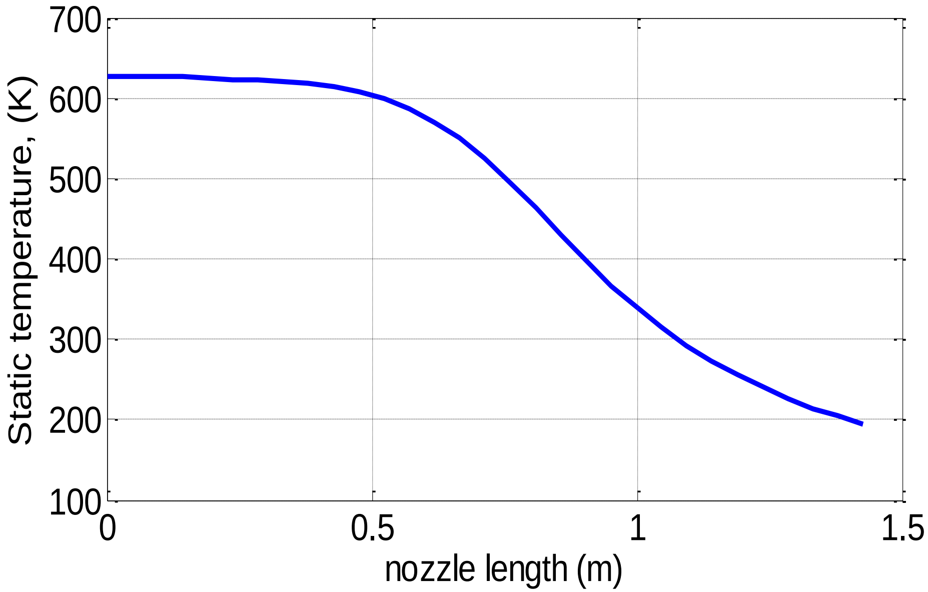
$$\overline{\left(\frac{\partial\rho}{\partial t}\right)}_i^{t+\Delta t} = -\frac{1}{A}\rho_i^{t+\Delta t}u_i^{t+\Delta t}\left(\frac{A_i-A_{i-1}}{\Delta x}\right) - u_i^{t+\Delta t}\left(\frac{\rho_i^{t+\Delta t}-\rho_{i-1}^t}{\Delta x}\right) - \rho_i^t\left(\frac{u_i^{t+\Delta t}-u_{i-1}^t}{\Delta x}\right)$$

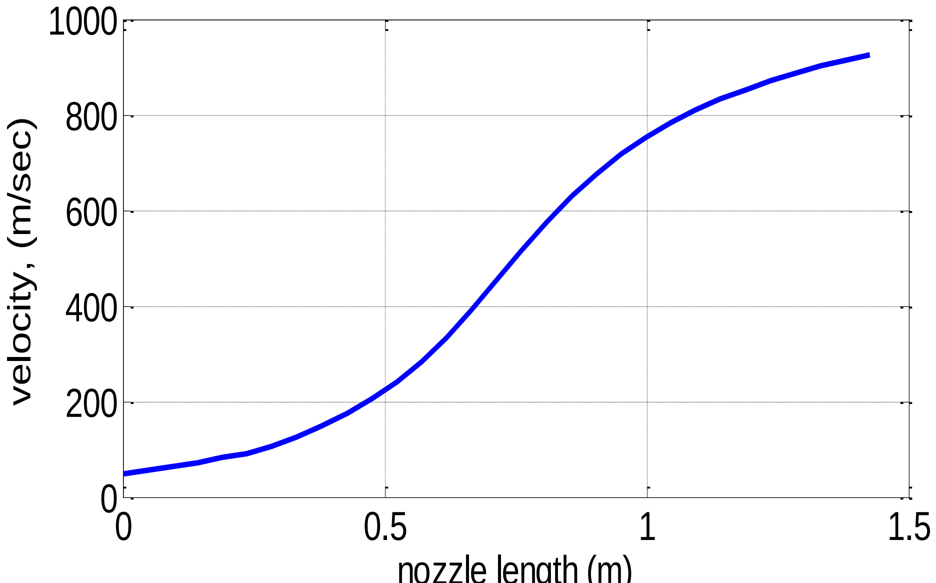
$$\rho_i^{t+\Delta t} = \rho_i^t + \frac{1}{2}\left[\left(\frac{\partial\rho}{\partial t}\right)_i^t + \overline{\left(\frac{\partial\rho}{\partial t}\right)}_i^{t+\Delta t}\right]\Delta t$$

Results
(so far steady state – no freq responses)



- Generic model verified against results reported in literature



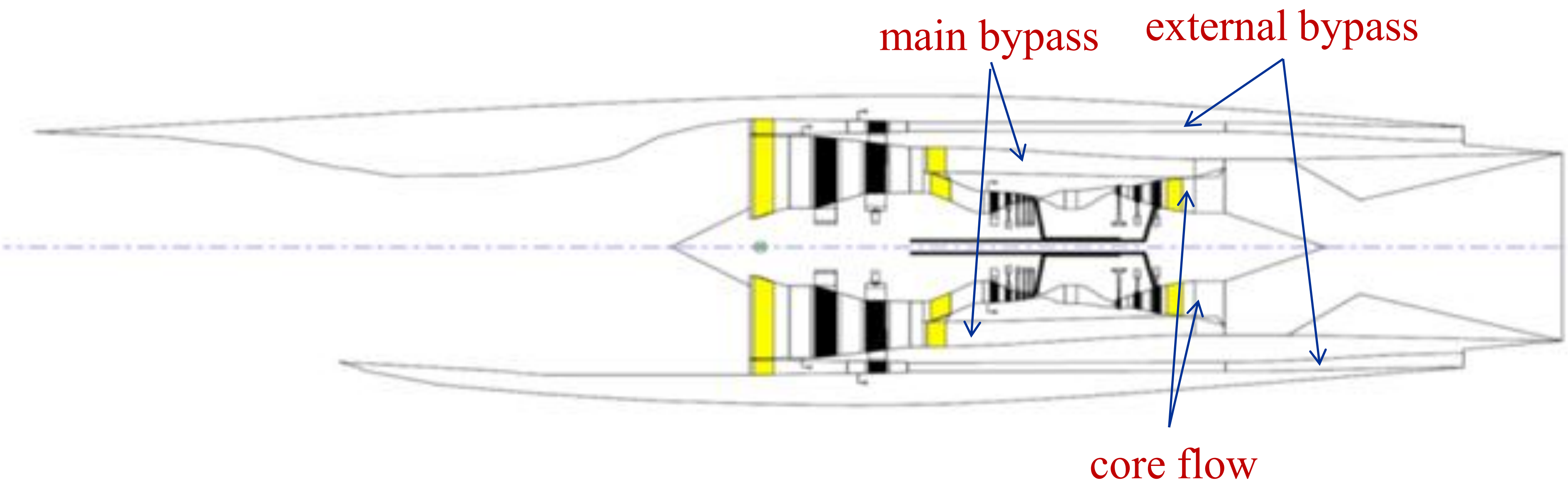


Variable Cycle Engine Model

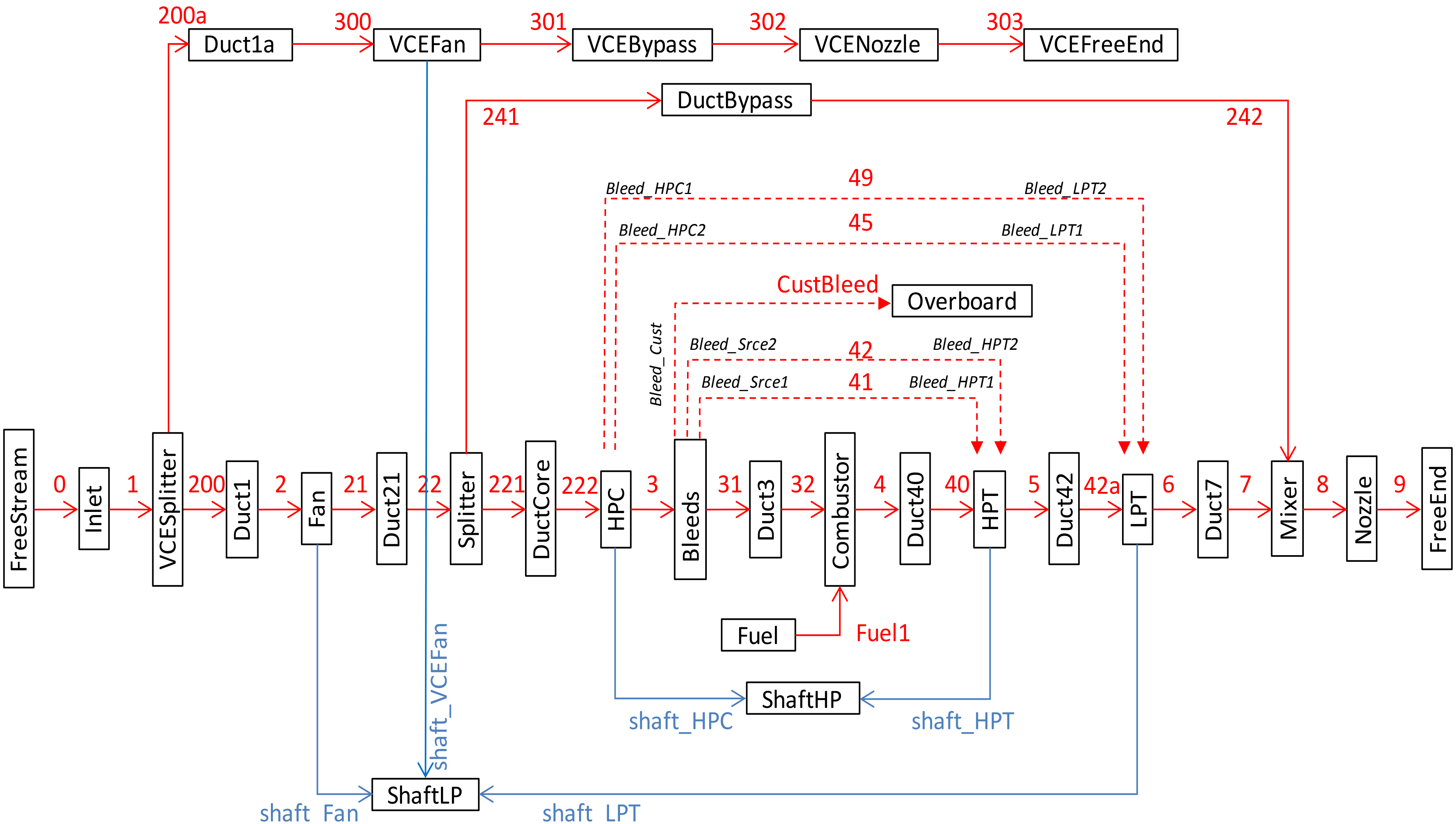
- Dual Spool variable cycle – High bypass at low altitudes to low bypass high altitudes

- Noise abatement for overland flight
  -- Through external bypass & through nozzle design

- Cycle analysis conducted in NPSS – provided geometries and component performance characteristics for dynamic model



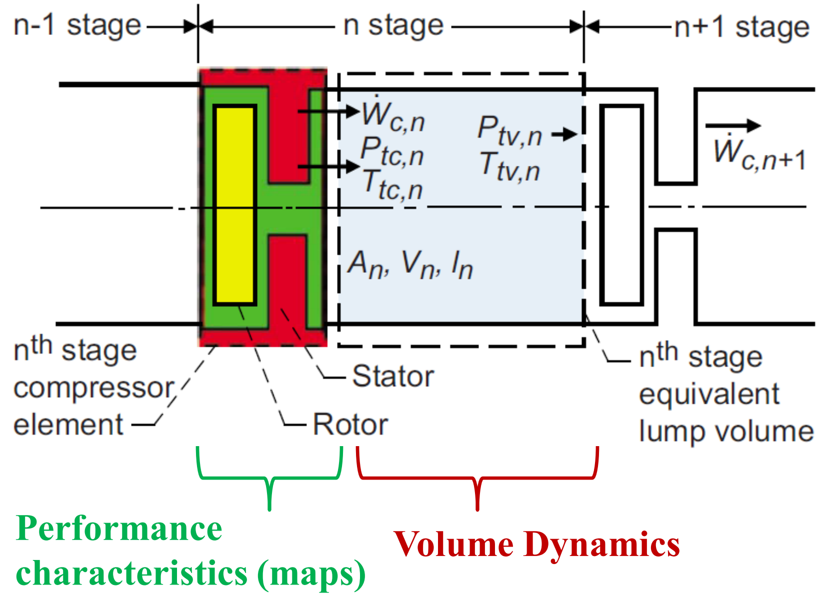
Variable Cycle Engine Model Components



Component Modeling - Roadmap & Approach

Development Roadmap

1. Original component models developed based on J85-13 engine
2. Many of J85-13 component models directly utilized for VCE w/ the appropriate maps and geometries
3. Some new component models developed (ducts, mixers, splinters, dual core) - **VCE V.1**
4. For some components need to develop detailed models – like CFD for inlet & nozzles
5. Need to develop fully operational engine (control schedules) – Methodology developed w/ J85-13
6. Parallel flow paths for distortion & boundary layer effects
7. Propulsion & ASE integration – Interfaces and controls



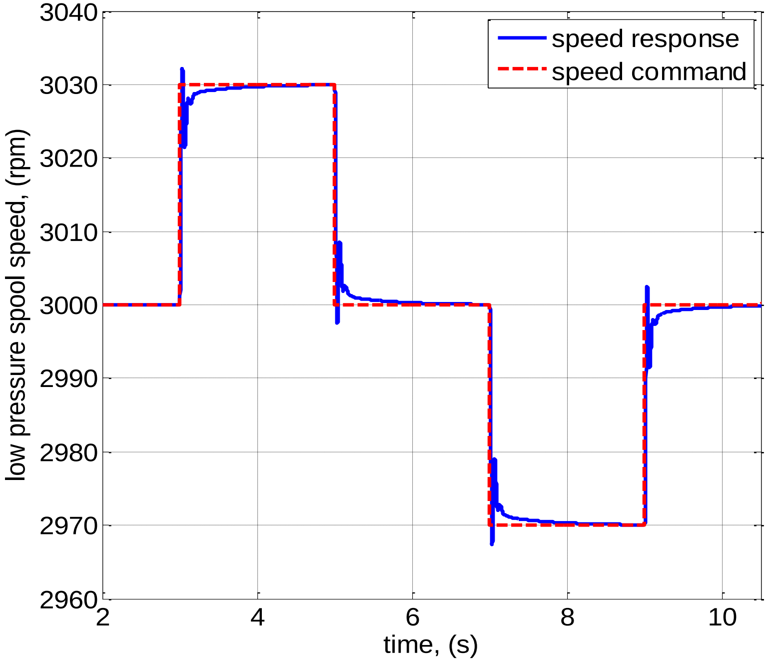
Continuity of mass, momentum & energy

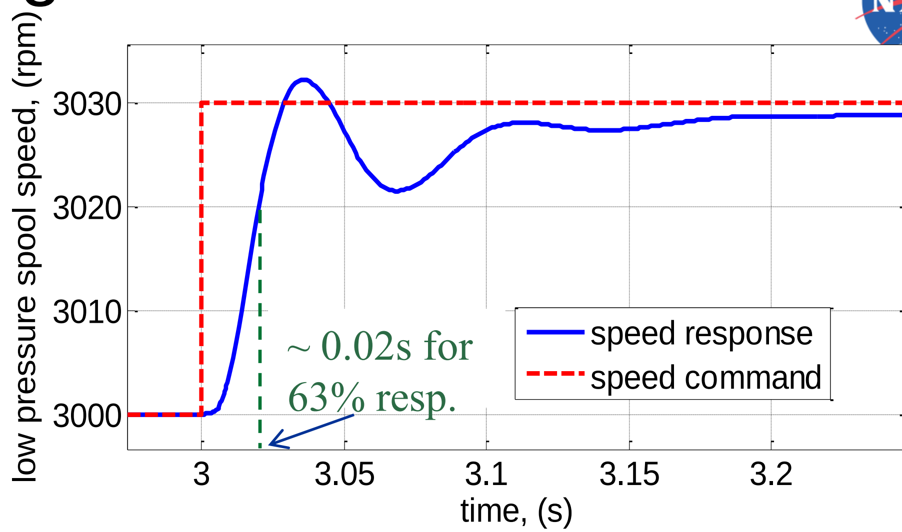
$$\frac{d}{dt}\rho_{\mathrm{sv},n} = \frac{1}{V_n}\left(\dot{W}_{c,n} - \dot{W}_{c,n+1} - \dot{W}_{b,n}\right)$$

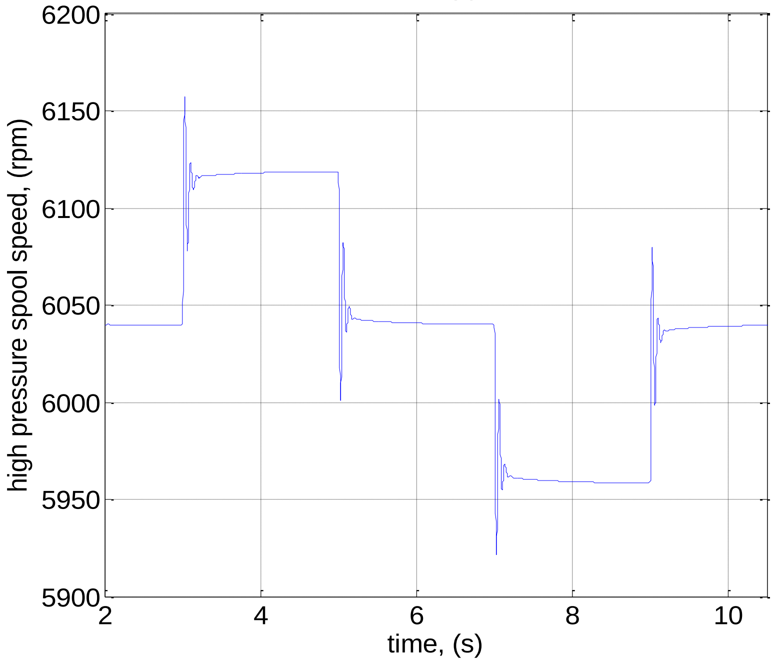
$$\frac{d}{dt}\dot{W}_{c,n} = \frac{A_n g}{l_n}\left(P_{\mathrm{tc},n} - P_{\mathrm{tv},n}\right)\left(1 + \frac{\gamma_{\mathrm{cp}} - 1}{2}M_n^2\right)^{-\gamma_{\mathrm{cp}}/(\gamma_{\mathrm{cp}}-1)}$$

$$\frac{d}{dt}\left(\rho_{\mathrm{sv},n}, T_{\mathrm{tv},n}\right) = \frac{\gamma_{\mathrm{cp}}}{V_n}\left(T_{\mathrm{tc},n}\dot{W}_{c,n} - T_{\mathrm{tv},n}\dot{W}_{c,n+1} - T_{\mathrm{tv},n}\dot{W}_{b,n}\right)$$

VCE Engine Results







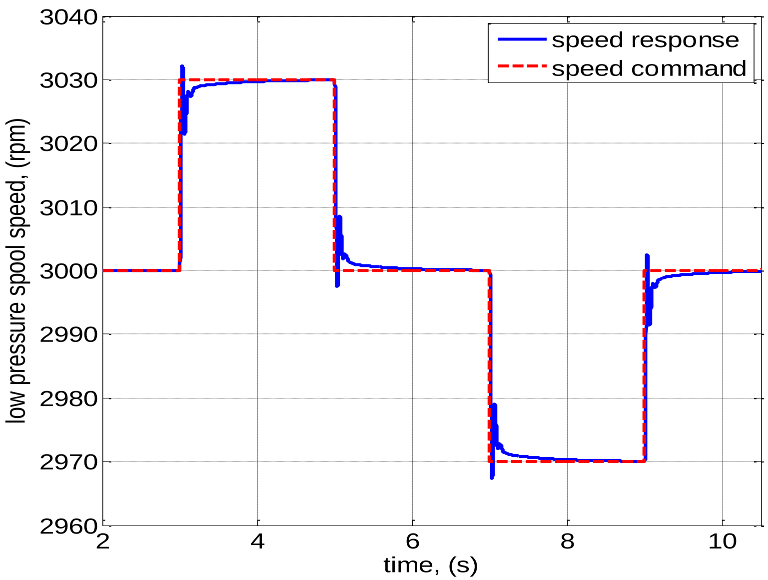
<u>Initial objective is VCE model development</u>

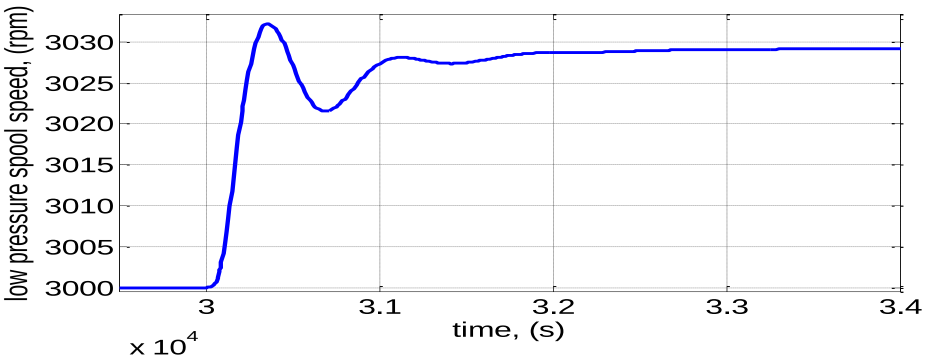
- Control design effort light; hold model together
  - -- But designed for higher bandwidth controls for disturbance attenuation

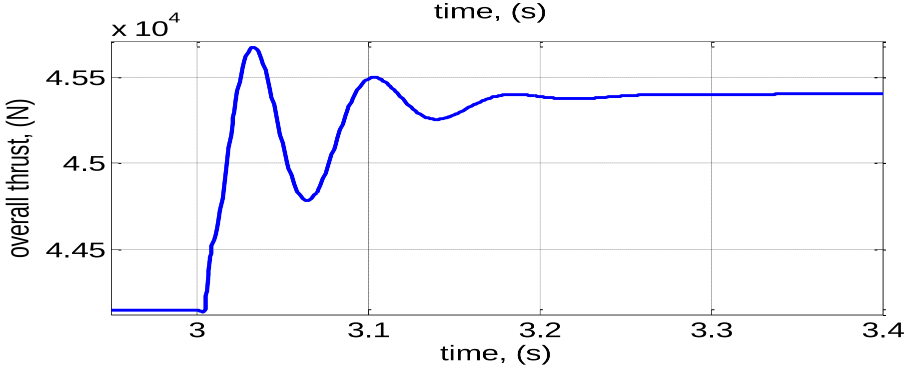
- Engine has higher response capability of ~ 70 rad/sec on high side (~40 rad/sec typically used)

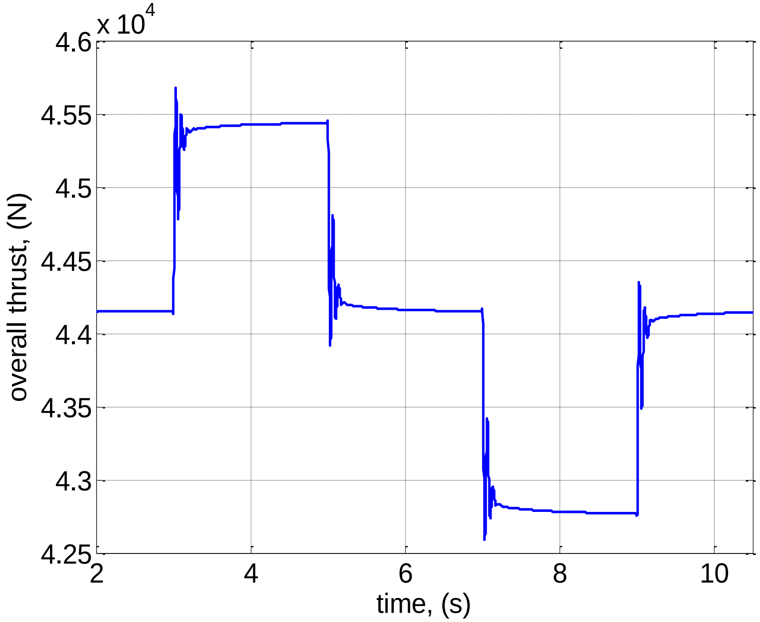
- Potential to use higher response capability to design for better disturbance attenuation, safety margins, and engine efficiency

VCE Engine Speed and Thrust









- Nominal VCE propulsion system thrust 44,100 N or 9,914 lbf
- A 1% change in fan speed causes 2.9% change in thrust
- Thrust response more underdamped – design of speed controller also needs to consider thrust response

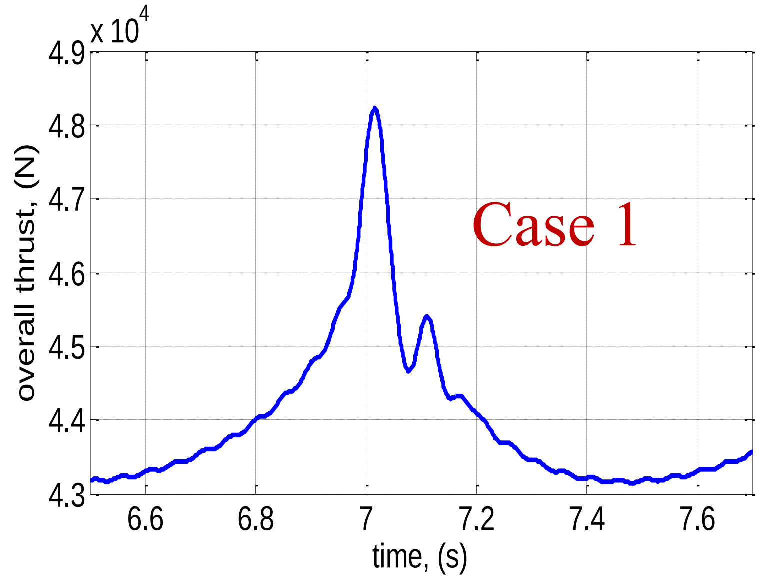
VCE Engine Atmospheric Disturbance and Thrust

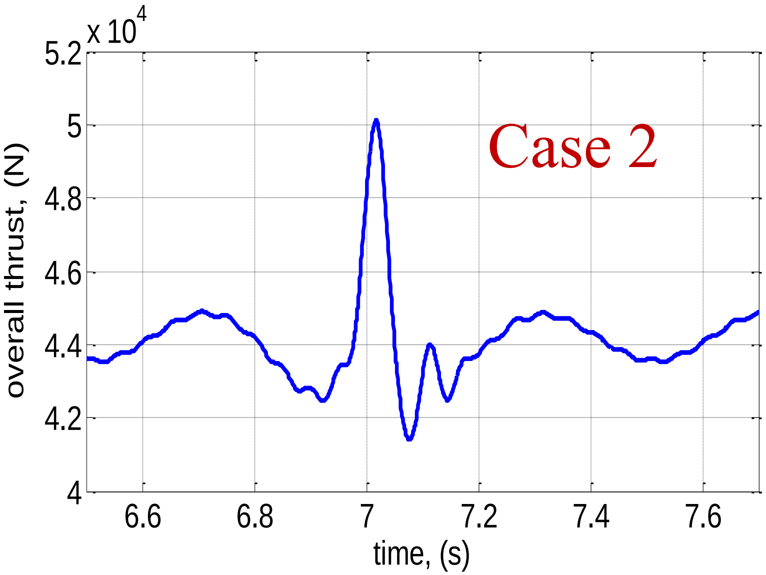
Thrust response w/ Atmospheric Disturbance

With no external compression inlet & no 1D CFD for nozzles

- Case 1; **eddy dissipation rate** 4x average of North Atlantic cruise altitudes; **integral length scale** typical (equivalent to atmospheric turbulence patch size of ~ 11 km); **max locally dissipating wind speeds** 80 mph
  -- Results in thrust variations up to ~ 5000 N or 1124 lb

- Case 2; eddy dissipation rate worst recorded; integral length scale typical; max dissipating wind speeds 150 mph
  -- Results in thrust variation up to ~ 9000N or 2024lb

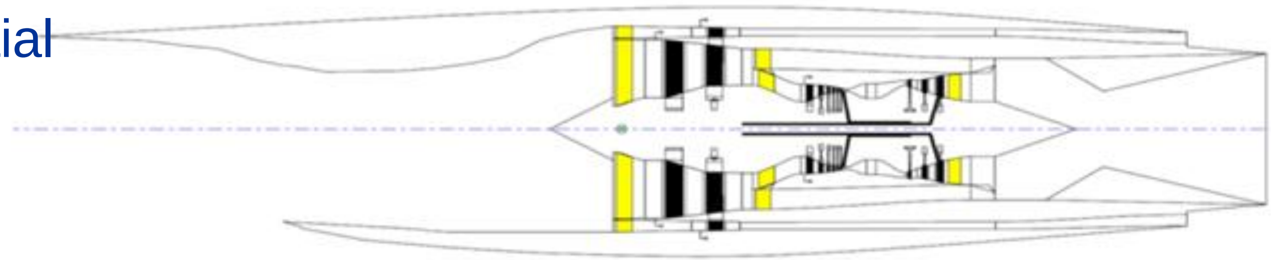




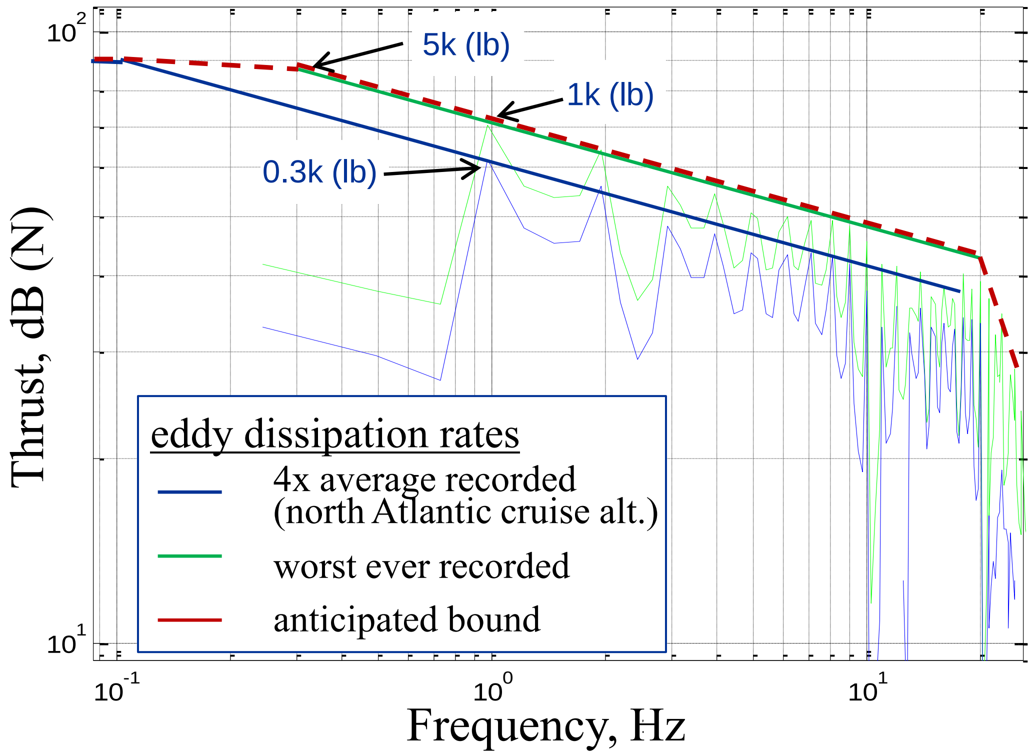
Variable Cycle Propulsion System Studies

Preliminary - Thrust Spectral for Coupling to AeroServoElastic (ASE) Modes

- Study based on V1. initial variable cycle engine modeling



- Atmospheric turbulence model w/ eddy dissipation rates & momentary wind gusts up to 180 mph



- Study shows potentially significant trust dynamics to warrant detailed APSE modeling and analysis

Future

- Develop complete integrated propulsion system variable cycle engine dynamic models and control designs
- Develop Integrated APSE system models, integrated vehicle controls, and conduct APSE studies
- Close integration between NPSS and APSE (already started)

Additional Possibilities of this Research

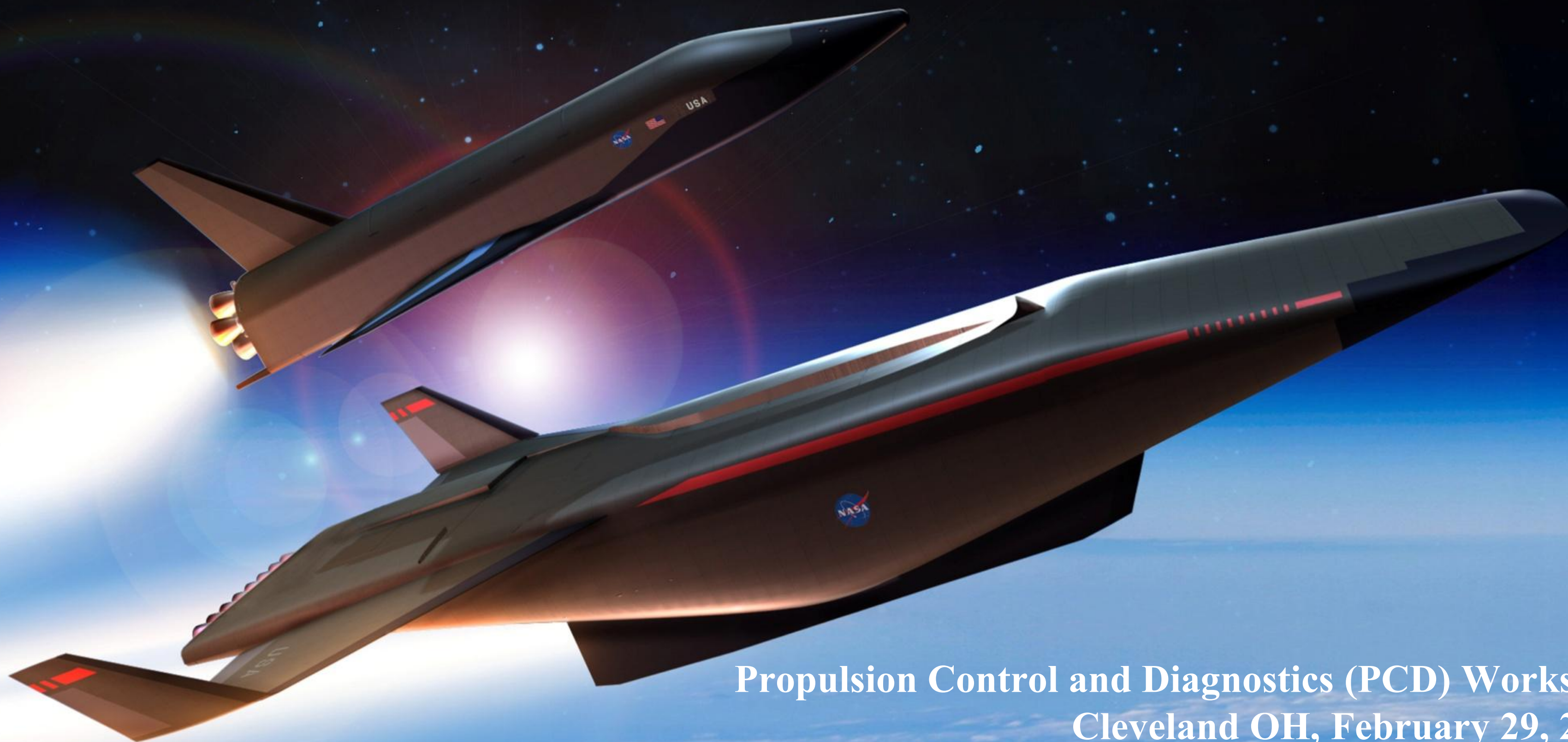
- Integrate w/ NPSS to develop a complete cycle deck design and verification package and controls development platform/Rig

- With gas dynamic model explore higher bandwidth controls to reduce stall margins and improve efficiency and design advanced controls to improve flight safety and operability

Combined Cycle Engine (CCE) Mode Transition

Fundamental Aeronautics – Hypersonic Project

Thomas J. Stueber
NASA Glenn Research Center
Cleveland, Ohio



Propulsion Control and Diagnostics (PCD) Workshop
Cleveland OH, February 29, 2012

Overview

Combined Cycle Engine (CCE) Mode Transition

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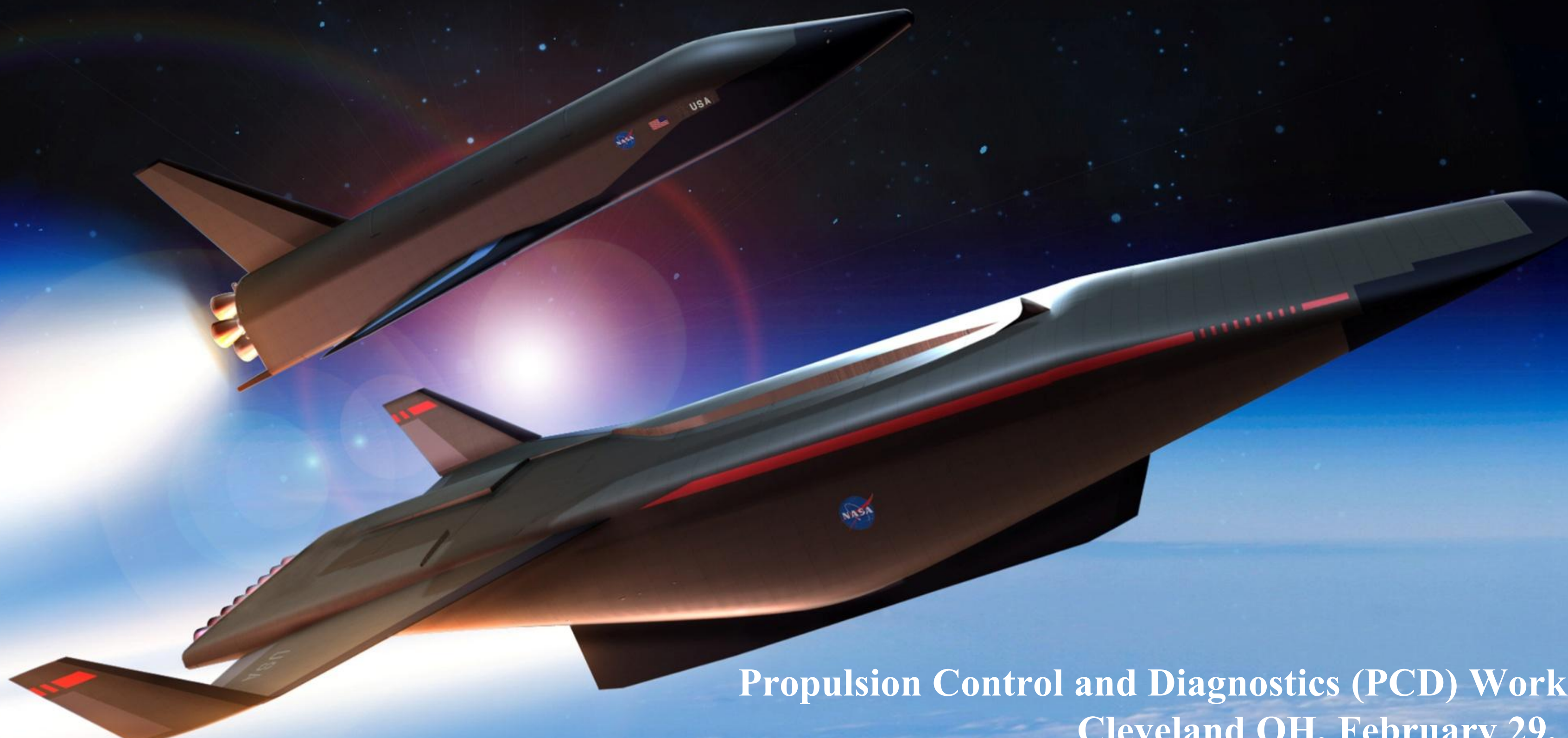

Propulsion Control and Diagnostics (PCD) Workshop
Cleveland OH, February 29, 2012

Team

- Communication, Instrumentation, and Controls Division / Research
  - Controls and Dynamics Branch (RHC)
    - Jeffrey T. Csank
    - Thomas J. Stueber
    - Randy Thomas
  - Digital Communications and Navigation (RHD)
    - Joseph A. Downey
    - Jennifer M. Nappier
    - Binh V. Nguyen
- Systems Engineering and Analysis Division / Engineering
  - Propulsion & Control Systems Engineering (DSS)
    - Dzu K. Le
    - Daniel R. Vrnak
- NASA Research Announcement 2005-2008 (NRA)
  - Spiritech Advanced Products Incorporated

Hypersonic Research Task Objective

Guidance Navigation and Control Team

- Design controllers for an air breathing propulsion system of a hypersonic vehicle to address the following issues:
  - Improve operability
  - Improve safety
  - Increase efficiency
  - Reduce cost

Roadmap to Controls Experiments

- Computational simulation development
- System identification (SysID) experiments with hardware
- Control design model (CDM) development
- Controls research and design
- Test controllers on computational simulation
- Controls experiments on hardware

Hypersonic: Combined Cycle Engine Mode Transition

- Overview of project activities (Stueber)
  - Propulsion system concept
  - Combined Cycle Engine (CCE) Large-Scale Inlet for Mode Transition Experiments (LIMX) introduction. **CCE-LIMX**
  - Simulation buildup
    - Controlling the Large Perturbation Inlet Simulation with Matlab Simulink software LAPIN-in-the-Loop
    - High Mach Transient Engine Cycle Code (HiTECC)
  - Wind tunnel experiments
- Hypersonic propulsion system simulation (Csank)
- CCE-LIMX wind tunnel experiments (Stueber)

Hypersonic: Combined Cycle Engine Mode Transition

- Overview
- Hypersonic Propulsion System Simulation Development
- CCE-LIMX Wind Tunnel Experiments

Propulsion System Concept

- Two stage to orbit (TSTO) reusable air breathing launch vehicle (RALV)
- Combined cycle engine (CCE) benefits
- TBCC propulsion system

Propulsion System Concept

- Two stage to orbit (TSTO) reusable air breathing launch vehicle (RALV)
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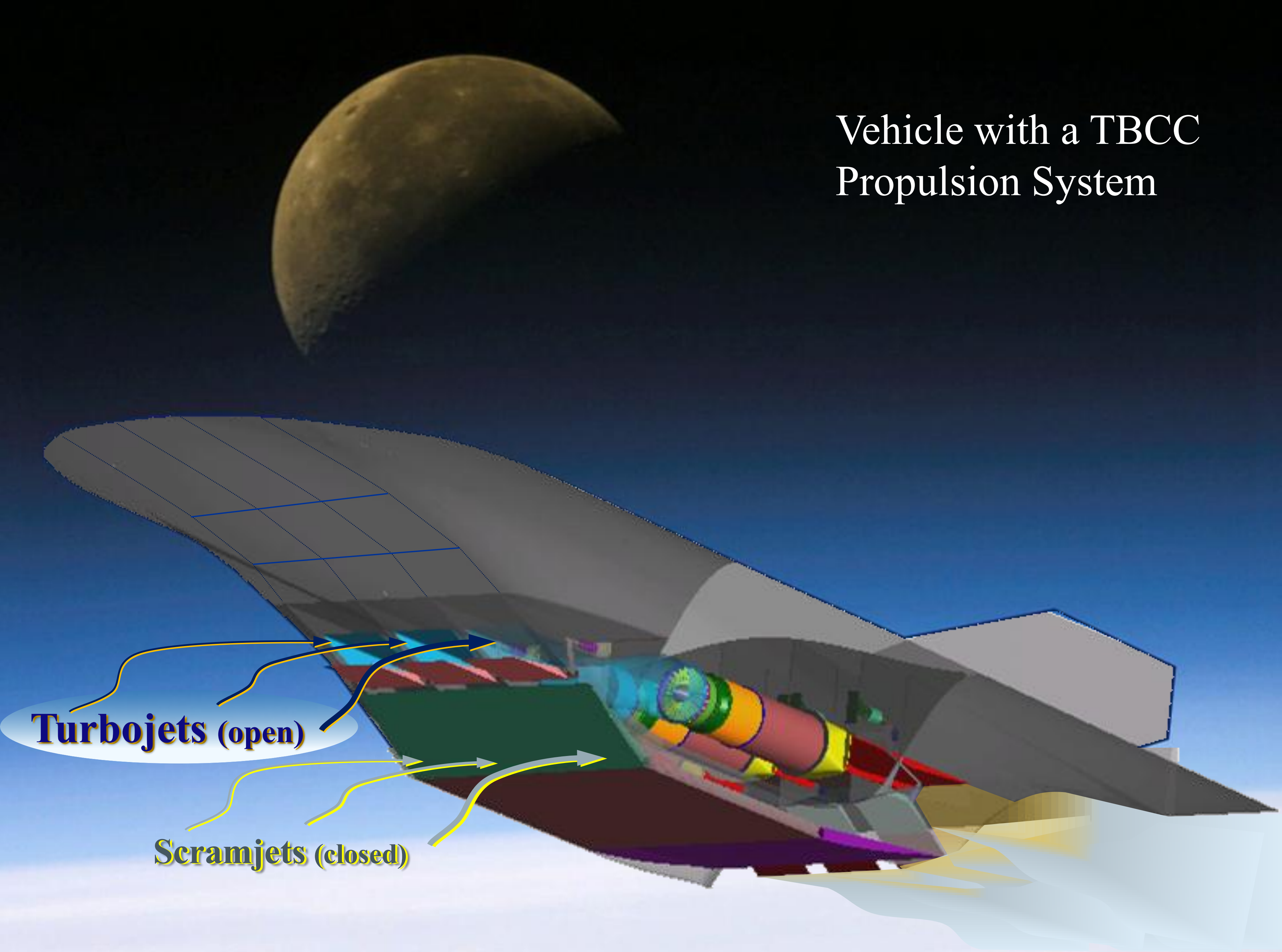
Turbine Based Combined Cycle

National Aeronautics and Space Administration

Hypersonics Project

Reusable Air Breathing Launch Vehicle (RALV) Concept

Two Stage To Orbit (TSTO)


Vehicle with a TBCC
Propulsion System
Turbojets (open)
Scramjets (closed)

TBCC Propulsion Benefits : Efficiency, Safety, Reliability

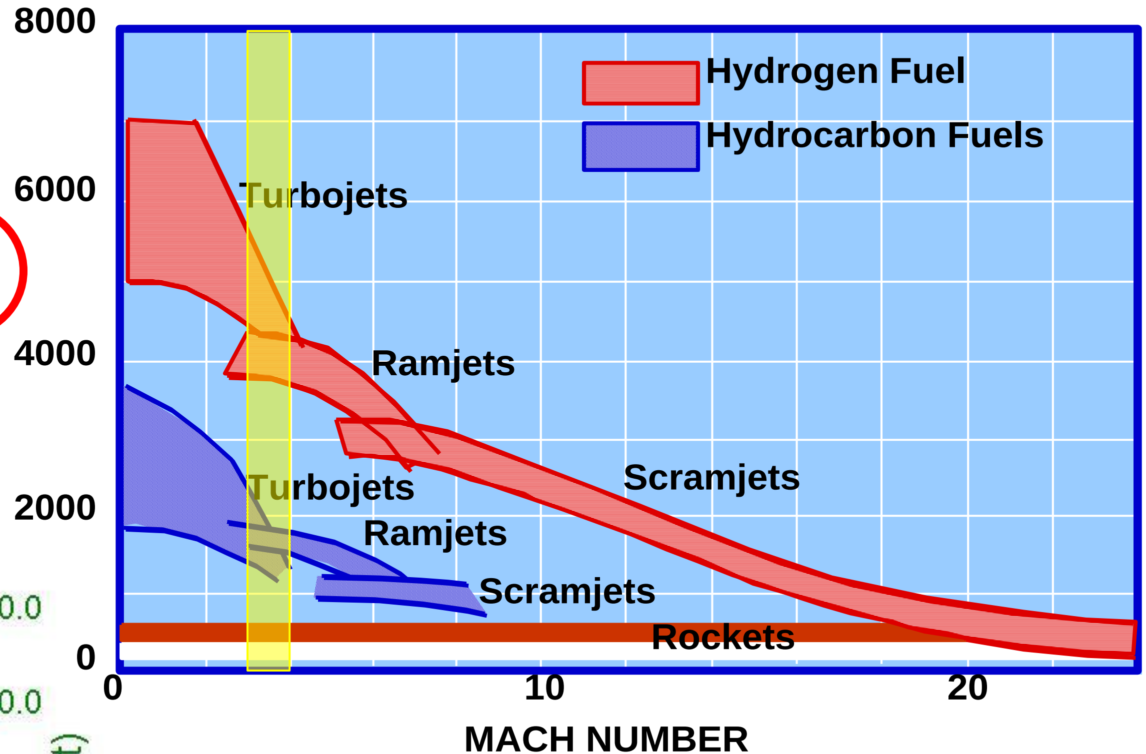
I_{SP} = *Thrust (lbf) per propellant mass flow rate*

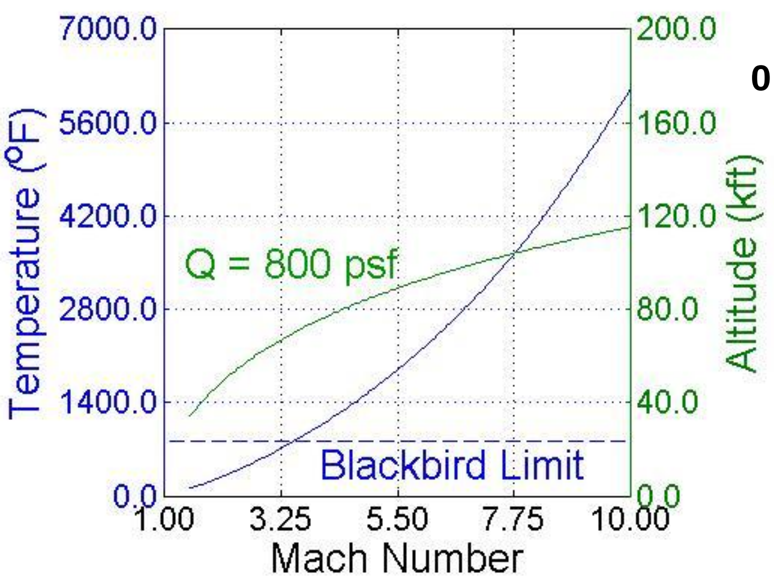
$$I_{SP} = \frac{F}{\dot{m} g_0}$$

$$g_0 = 32.174 \text{ ft/sec}^2$$

I_{sp}

Specific Impulse





- **Horizontal takeoff and landing enhances launch, flight and ground operability**
  - ✓ **Benign ascent abort/engine out**
  - ✓ **Launch pad not needed**
  - ✓ **Flexible operations & quick turn around time (Aircraft like operations)**

TBCC Propulsion Benefits : Efficiency, Safety, Reliability

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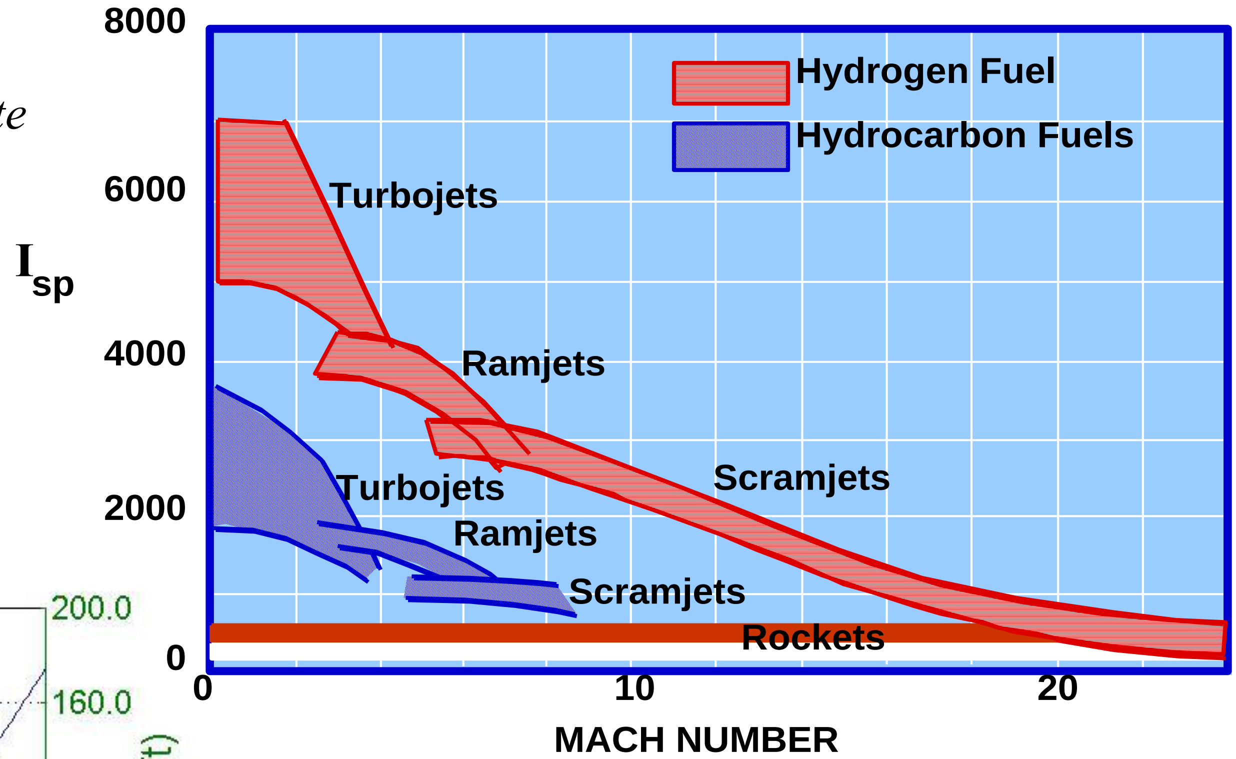

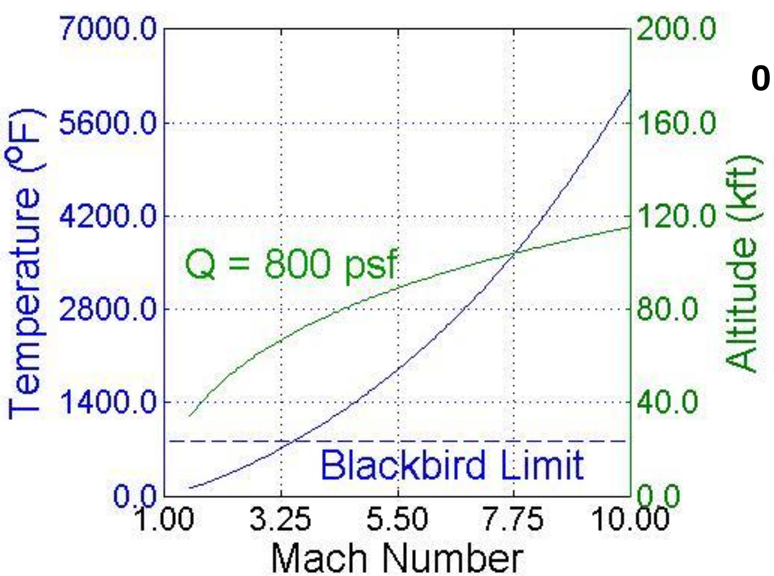

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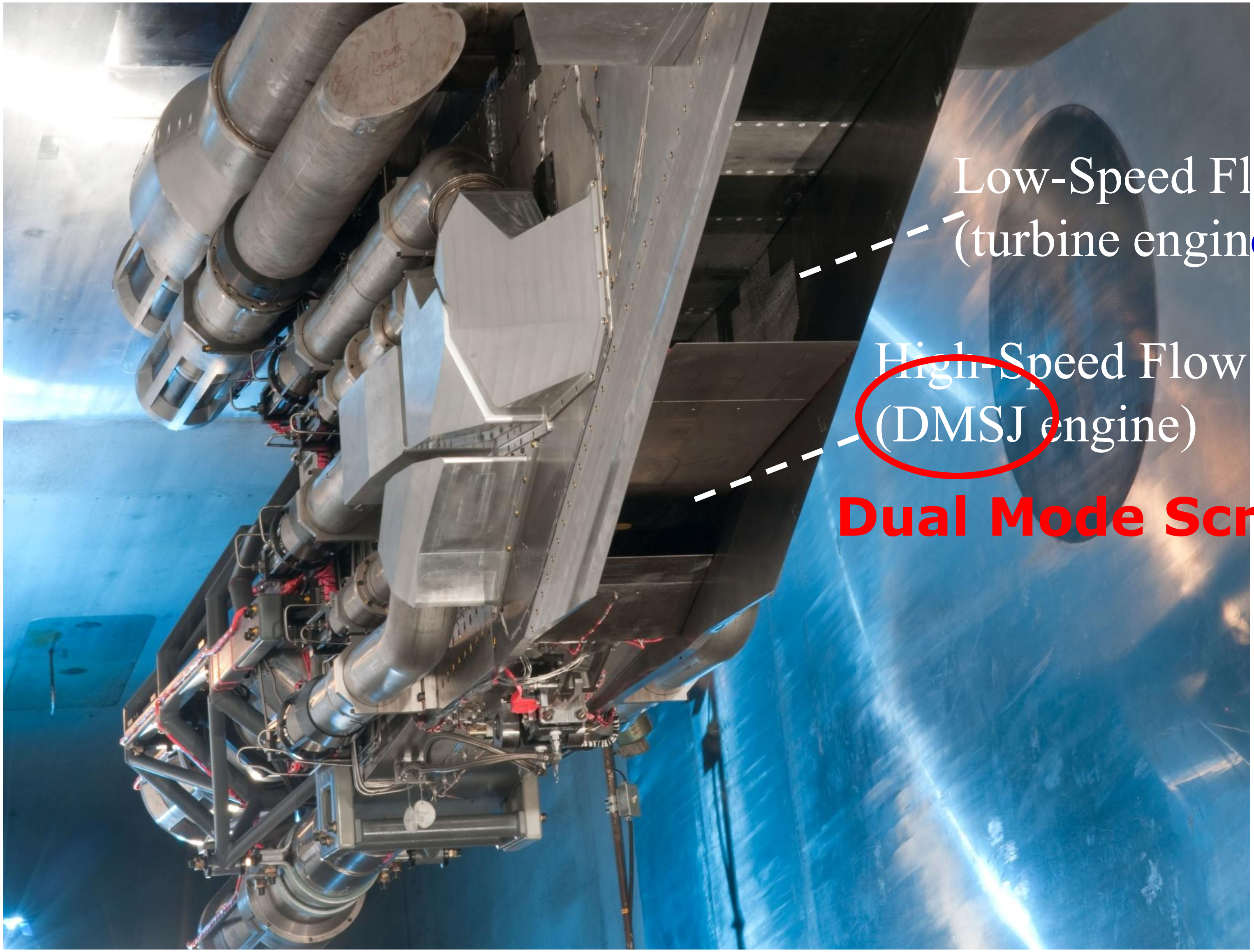
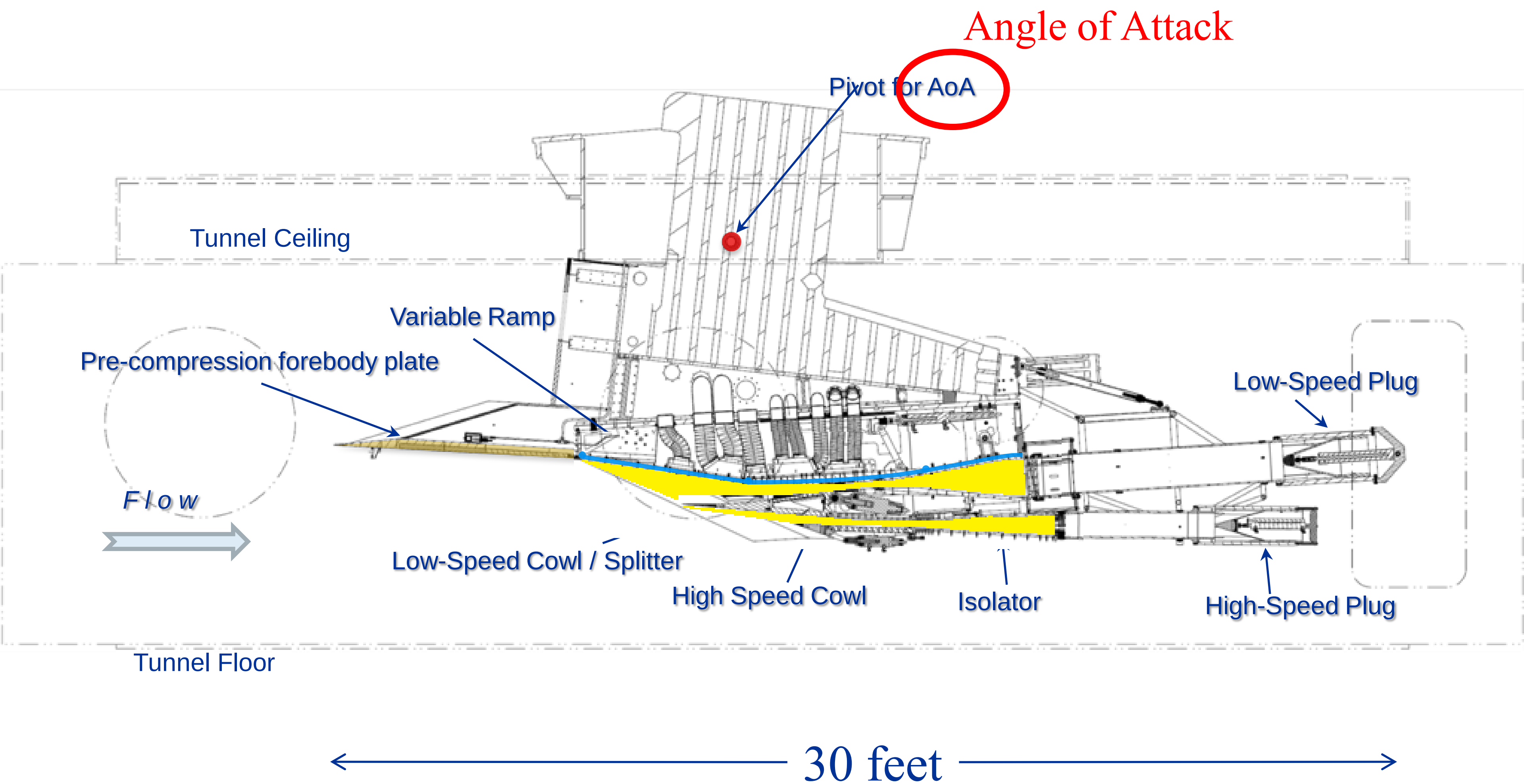
Combined Cycle Engine (CCE)
Large-Scale Inlet for Mode Transition Experiments (LIMX).
CCE-LIMX

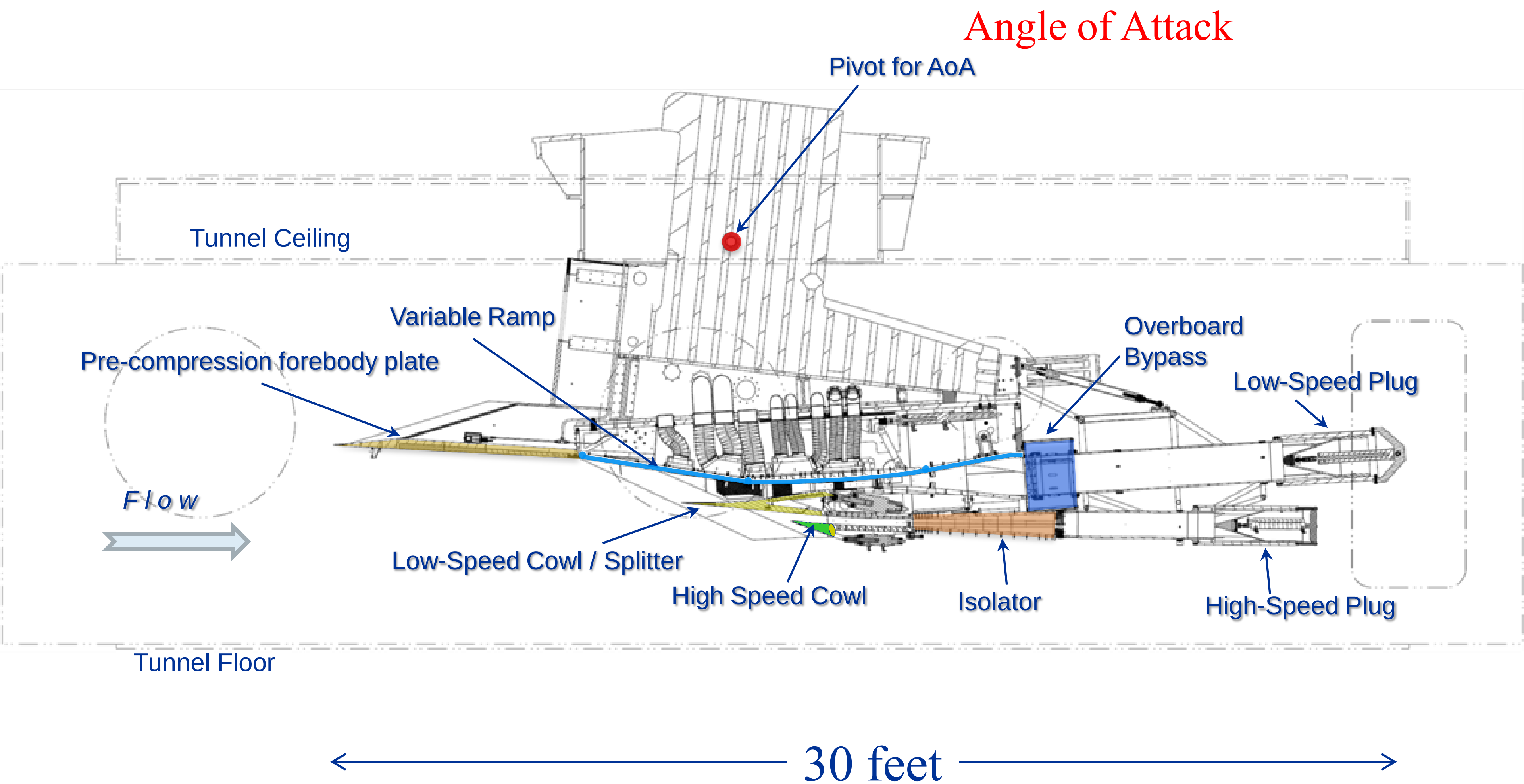
CCE-LIMX Model



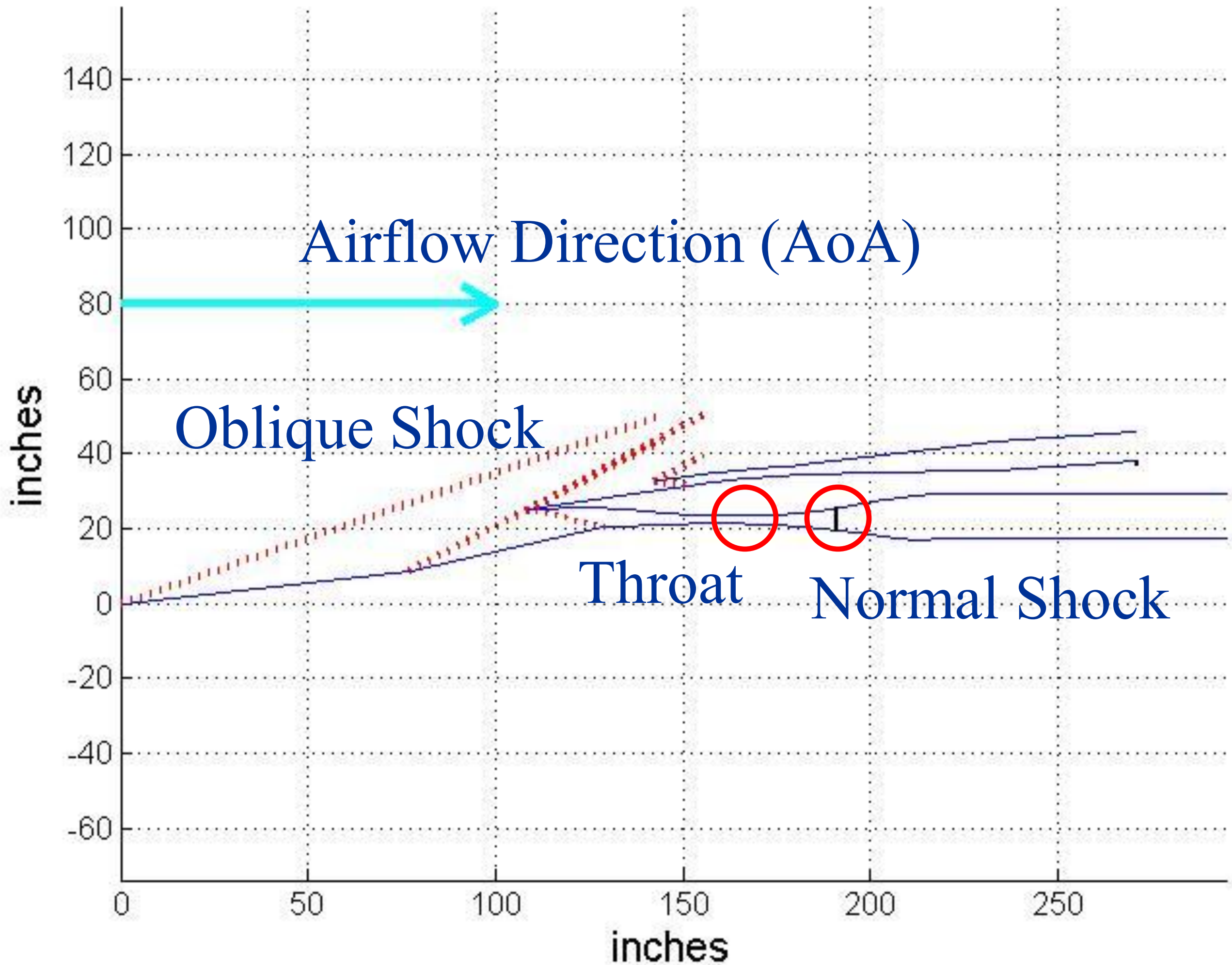
CCE-LIMX Model Features



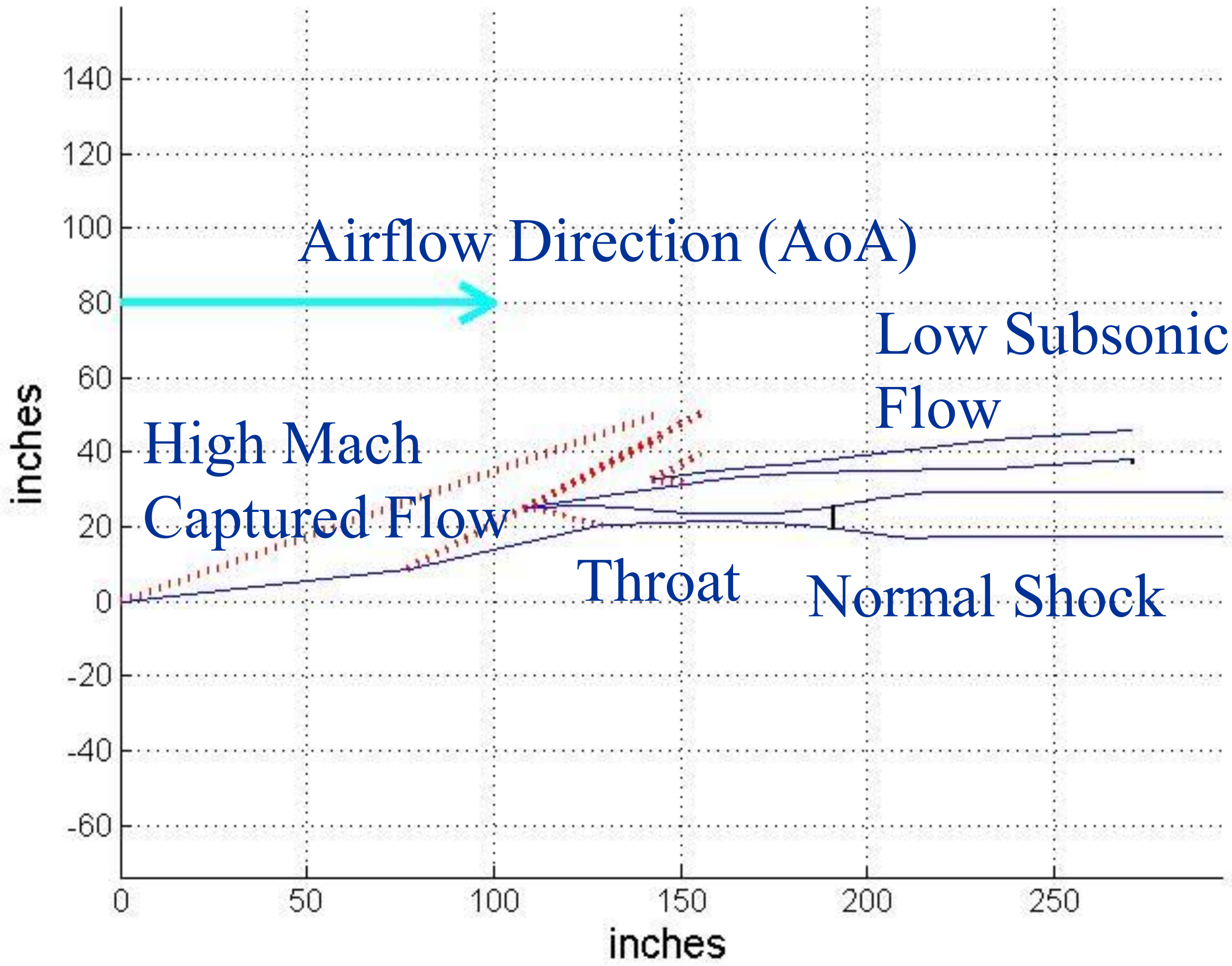
CCE-LIMX Model Features



CCE-LIMX Inlet Terminology



CCE-LIMX Inlet Terminology



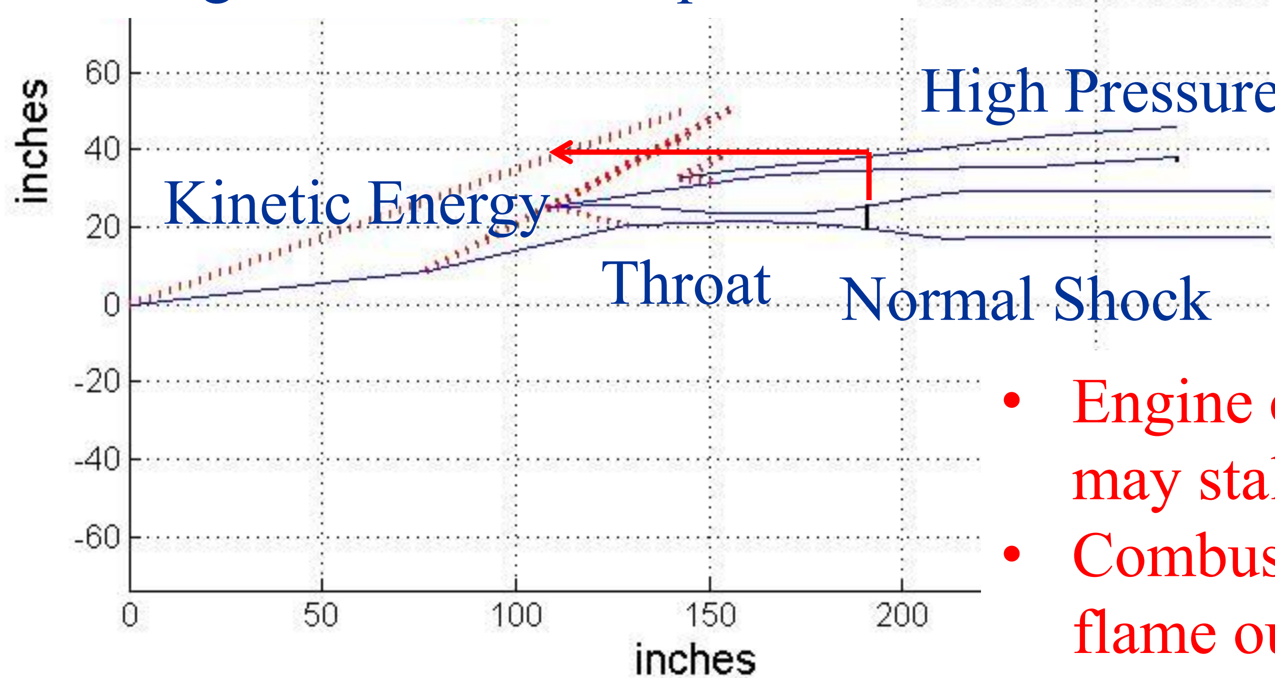
CCE-LIMX Inlet Terminology

Causes of unstart:

- Compressor stall
  - Rapid throttle change
  - Afterburner ignition
  - Inlet airflow distortion
  - Rapid changes in inlet air temperature

UnStarted Inlet

~~High mass flow rate~~
~~High pressure recovery~~
~~Low drag~~
~~Low distortion~~



- Engine compressor may stall
- Combustor may flame out

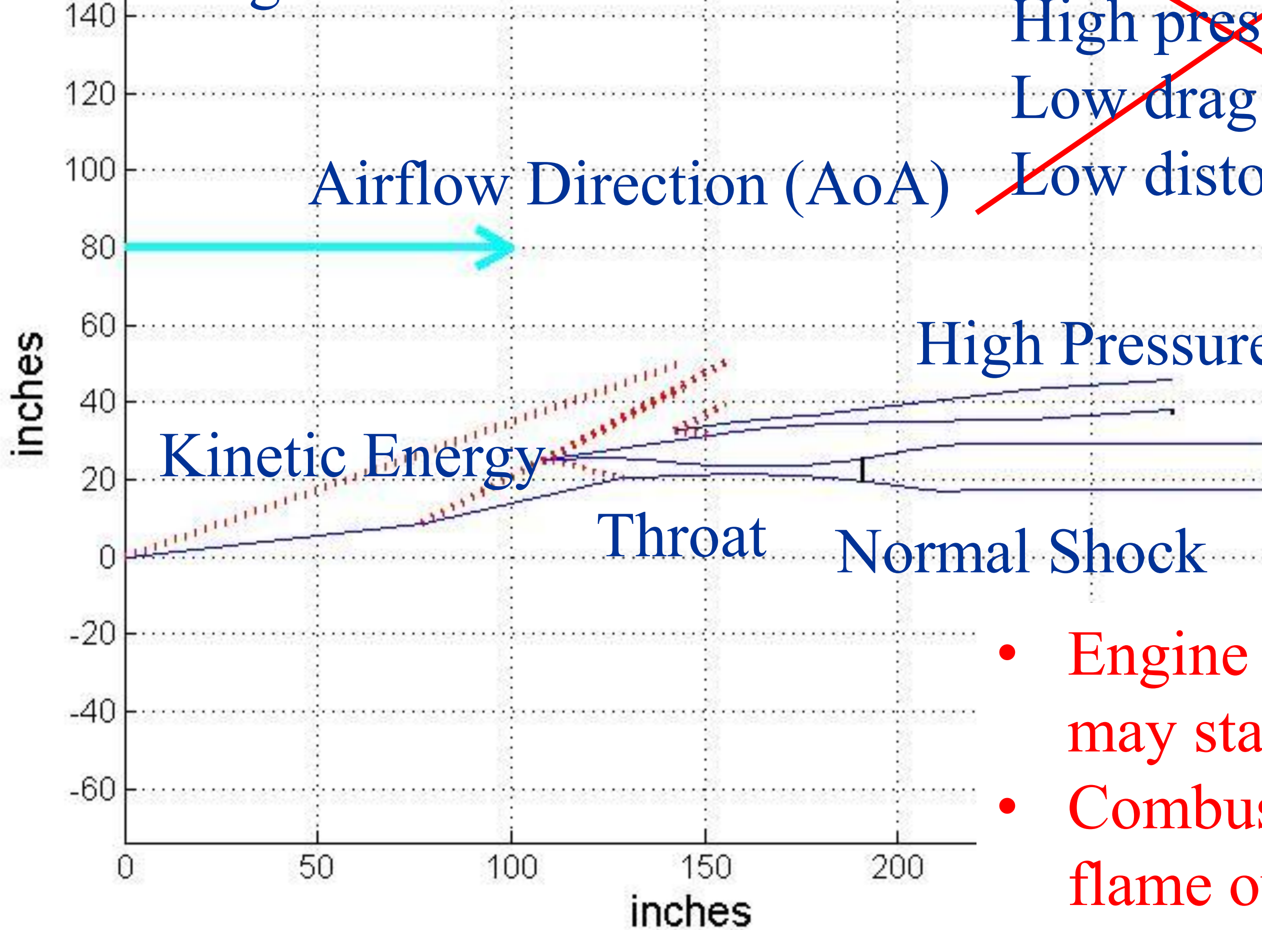
CCE-LIMX Inlet Terminology

Causes of unstart:

- Compressor stall
- Free stream changes

UnStarted Inlet

~~High mass flow rate~~
~~High pressure recovery~~
~~Low drag~~
~~Low distortion~~



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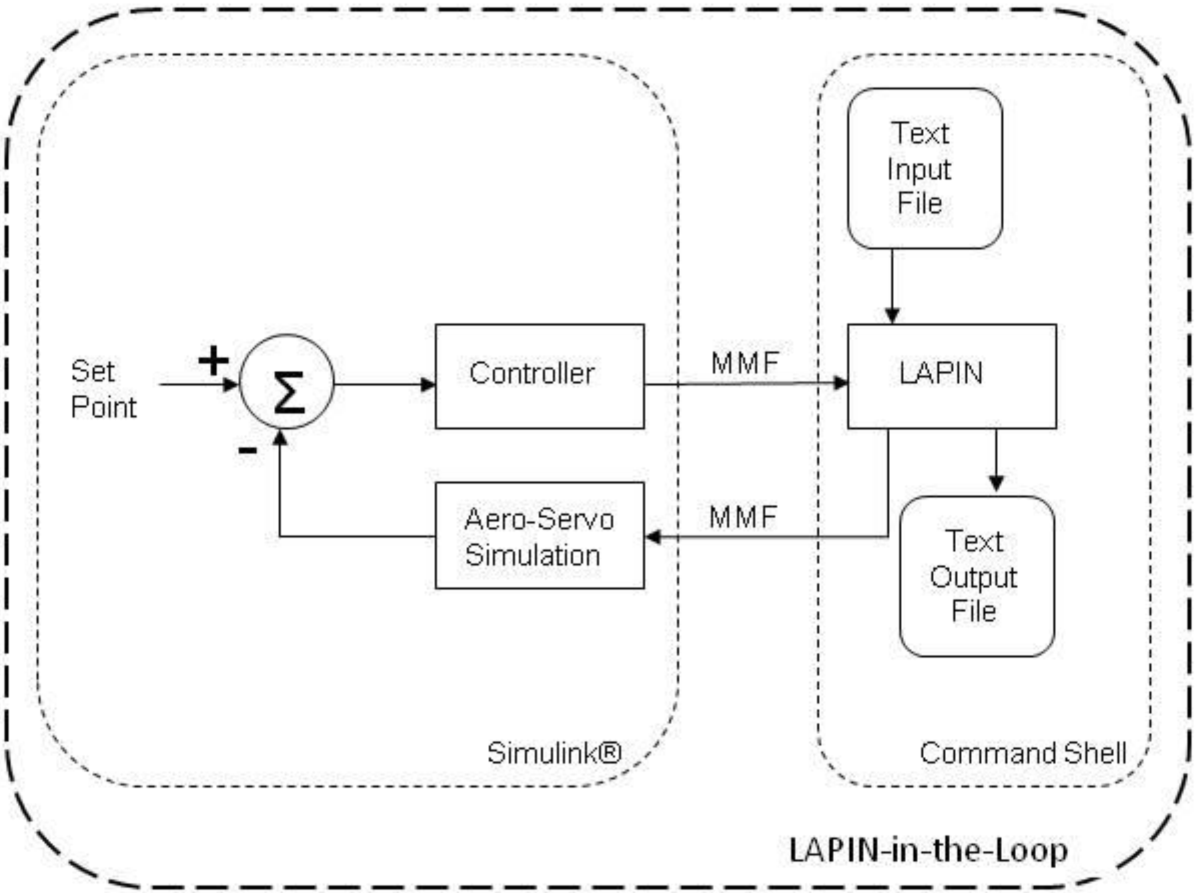
Computational Simulations

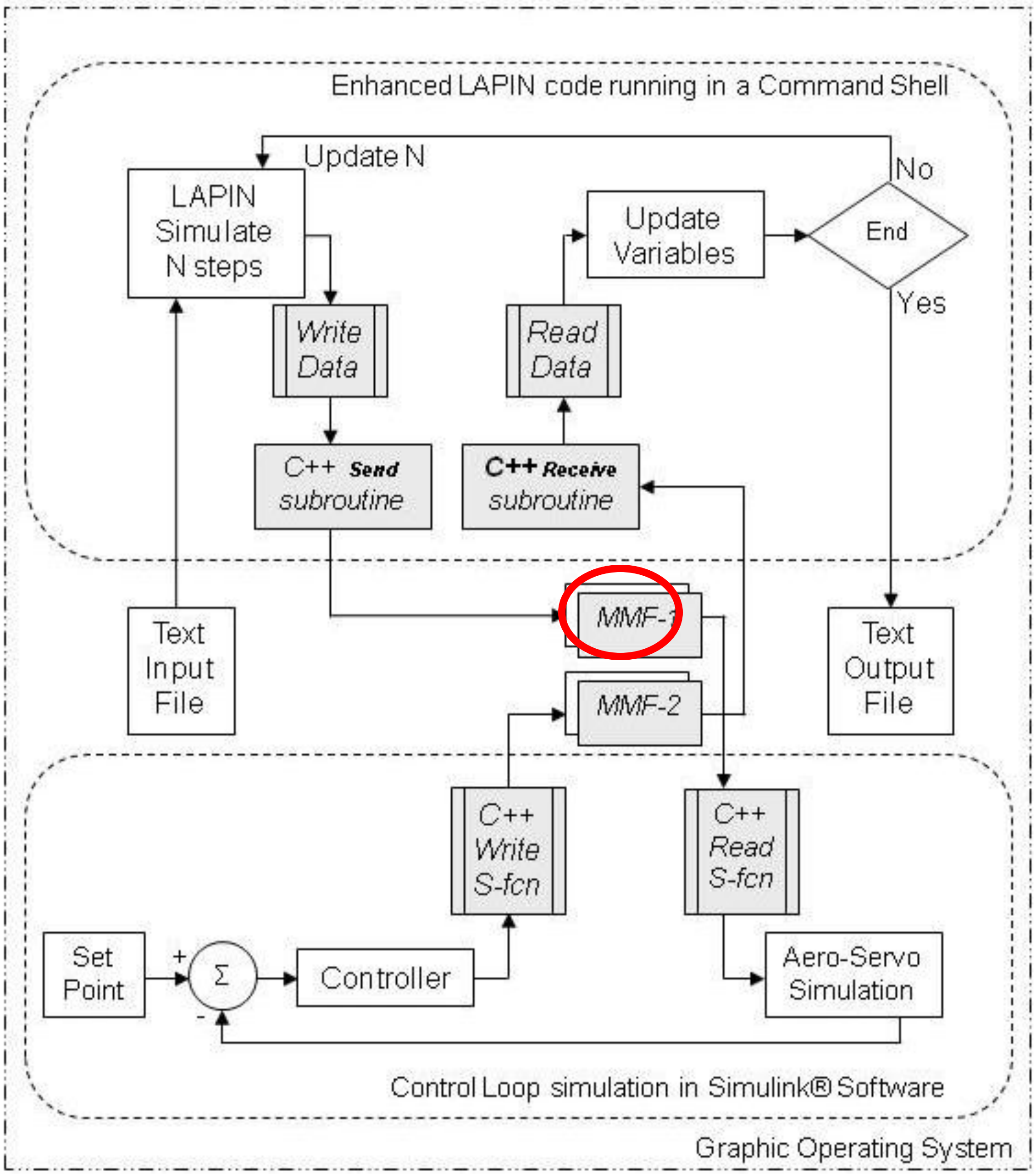
- LAPIN-in-the-Loop
- HiTECC (Jeffrey Csank)

LAPIN-in-the-Loop

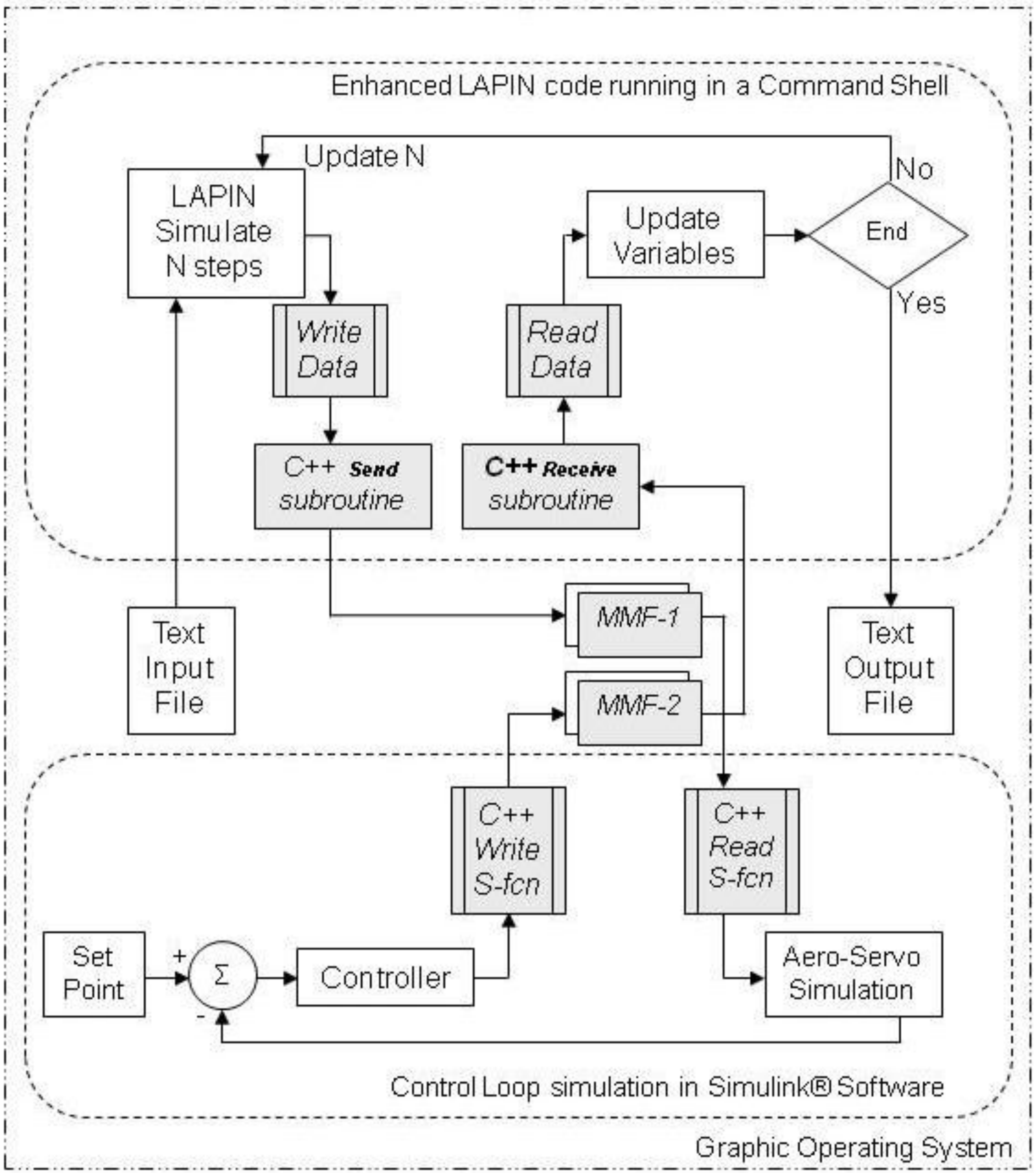


LAPIN-in-the-Loop

Memory Mapped File



LAPIN-in-the-Loop



CCE Inlet Wind Tunnel Experiments

- CCE-LIMX hardware testing is conducted in the following four phases:
  - Phase 1 Inlet characterization and performance testing
    - Static inlet operating points
    - Mode transition schedule
  - Phase 2 System identification
    - Step response analysis
    - Sinusoidal sweep response analysis
  - Phase 3 Controls testing
    - Disturbance rejection testing
    - Controlled mode transition
  - Phase 4 Propulsion system testing
    - Turbine engine for LSFP
    - Dual-mode combustor for HSFP

CCE Inlet Wind Tunnel Experiments

- CCE-LIMX hardware testing is conducted in the following four phases:
  - Phase 1 Inlet characterization and performance testing
    - Static inlet operating points
    - Mode transition schedule
  - Phase 2 System identification
    - Step response analysis
    - Sinusoidal sweep response analysis
  - Phase 3 Controls testing
    - Disturbance rejection testing
    - Controlled mode transition
  - Phase 4 Propulsion system testing
    - Turbine engine for LSFP
    - Dual-mode combustor for HSFP

Low-Speed Flow Path

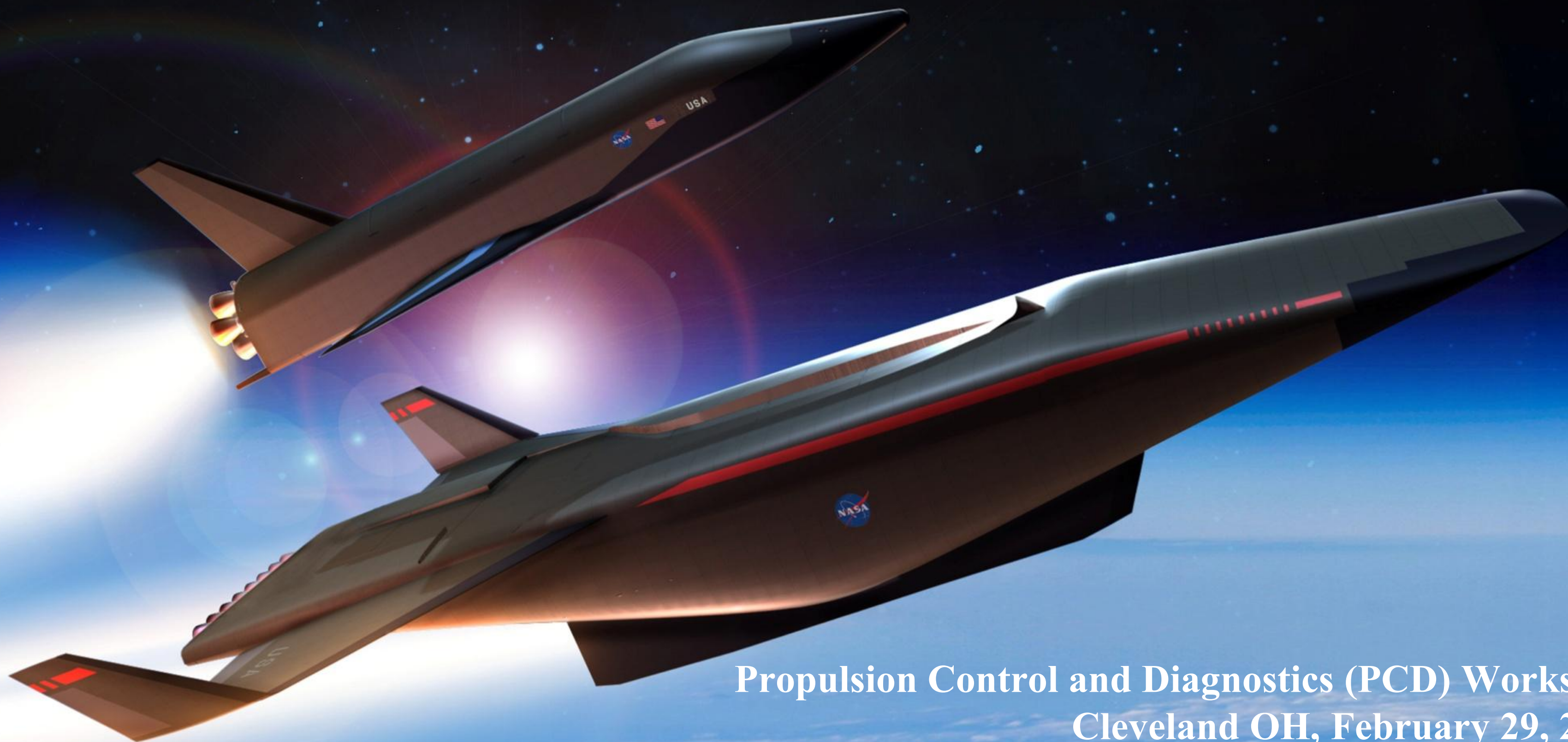
High-Speed Flow Path

Hypersonic Propulsion System Simulation Development

Hypersonic Combined Cycle Engine (CCE) Mode Transition

Fundamental Aeronautics – Hypersonic Project

Jeffrey Csank
NASA Glenn Research Center
Cleveland, Ohio



Propulsion Control and Diagnostics (PCD) Workshop
Cleveland OH, February 29, 2012

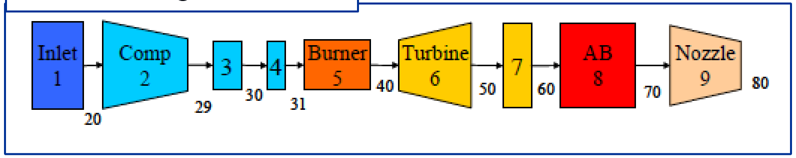
HiTECC Simulation

- **Hi**gh Mach **T**ransient **E**ngine **C**ycle **C**ode (HiTECC)
- Simulation package initially developed by SPIRITECH Advanced Products, Inc.
- Developed under the Hypersonic Project, Guidance Navigation and Control (GN&C) task.
  - Develop tools and procedures for experimental data analysis, control design and evaluation
  - HiTECC used to design and evaluate candidate mode transition/shock position control algorithms

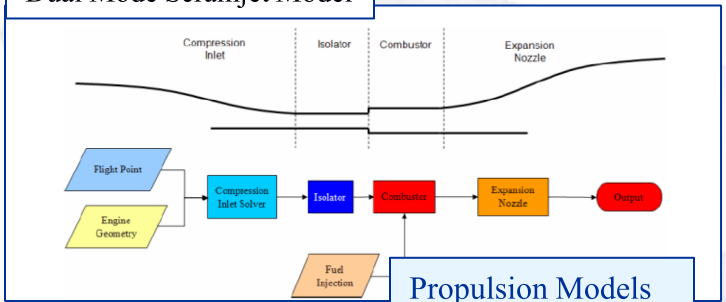
HiTECC Objectives

- Demonstrate all modes of operation of a turbine based combined cycle (TBCC) propulsion system
  - Afterburner, turbine engine, dual mode scram jet
  - Simulate the mode transition sequence of events
- Designed to be generic and modular
  - Inlet geometry is described using the MathWorks® SimScape™
  - Can be used to convert CAD Drawing to Simulink® model file
  - Fast prototyping of inlet designs

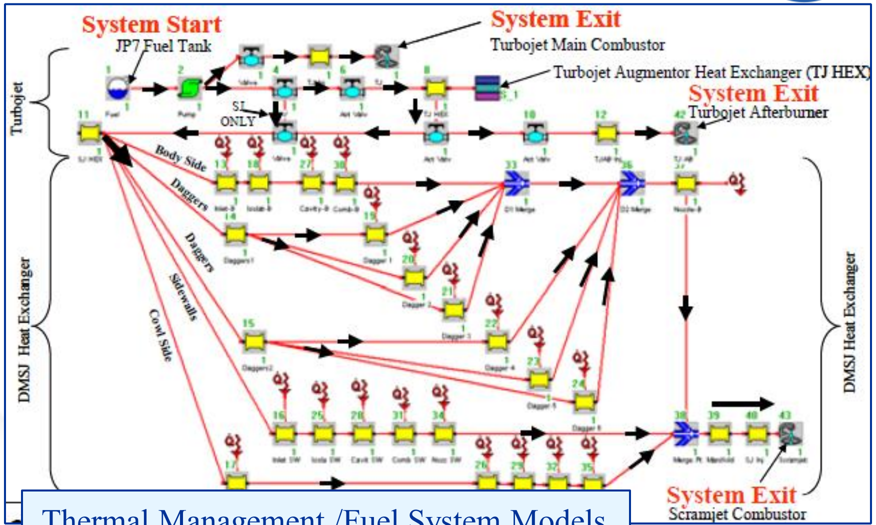
Turbo Jet Engine Model



Dual Mode Scramjet Model



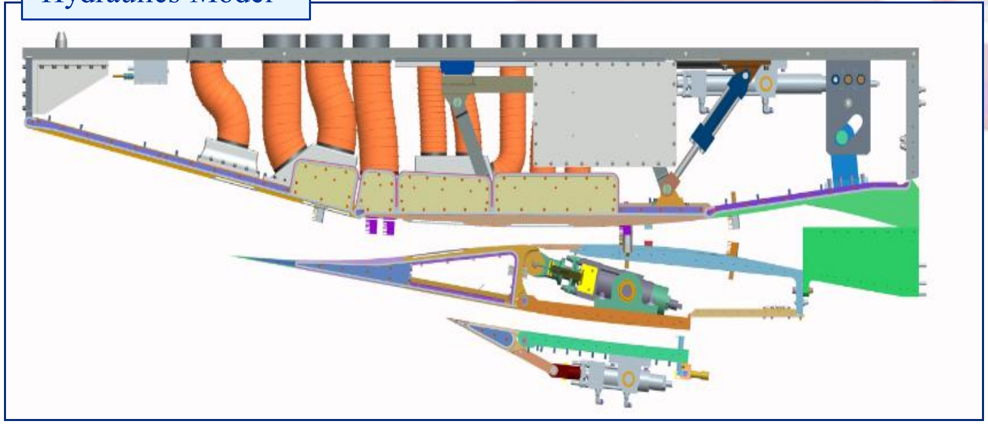
Propulsion Models



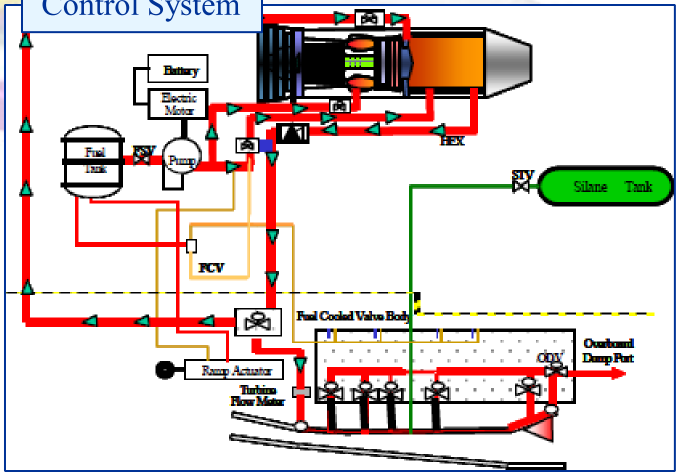
Thermal Management /Fuel System Models

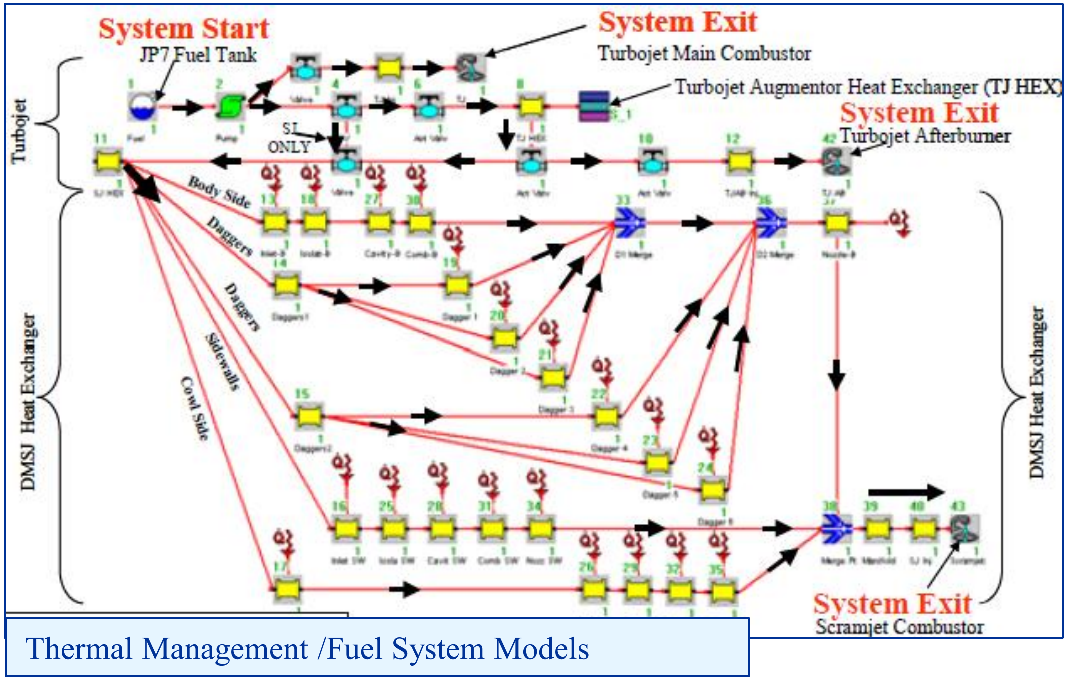
High Mach Transient Engine Cycle Code (HiTECC)

Hydraulics Model



Control System





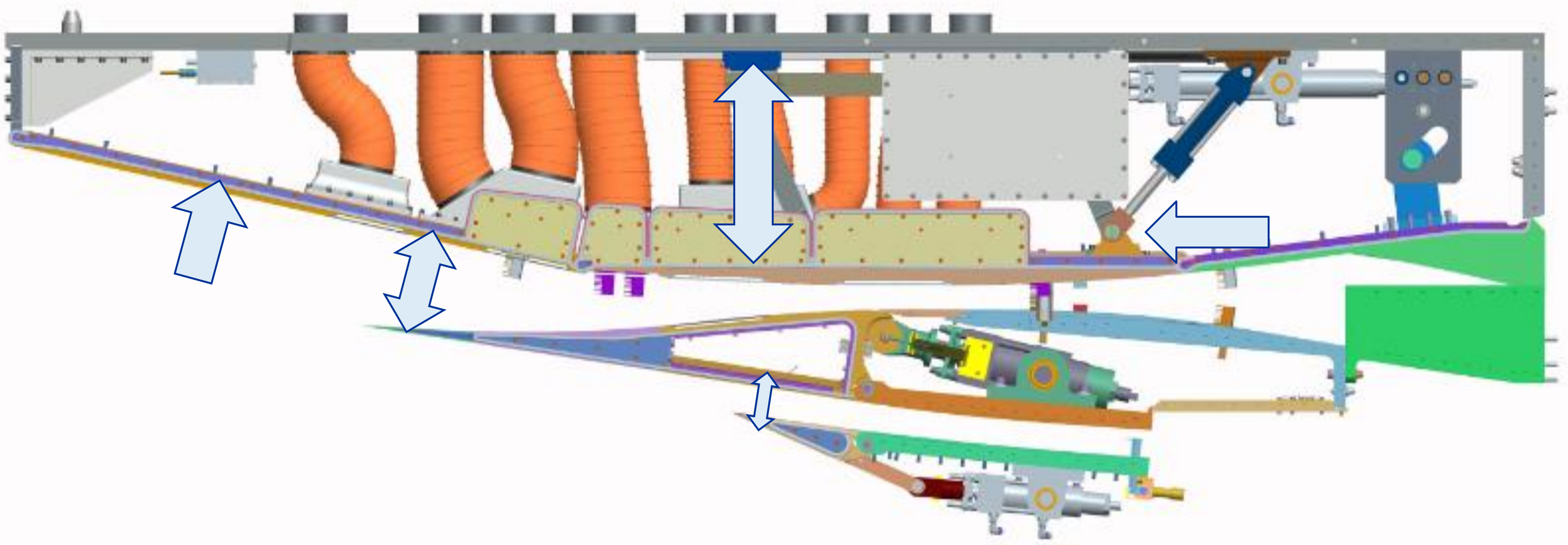
•Simulates fuel flow, fluid energy, and thermal energy transfer for both the LSFP and HSFP

•Couples a transient flow model and a transient thermal model

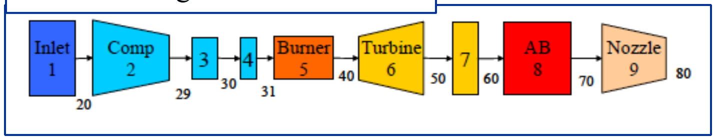
•One-dimensional compressible flow solver allows a variety of fuels, including hydrogen, to be modeled

- Simulates the kinematic features of the variable inlet and nozzle for both flow paths
- Models the dynamic response of the hydraulic fluid
- Models for the power storage and generation for pumping the hydraulic fluid

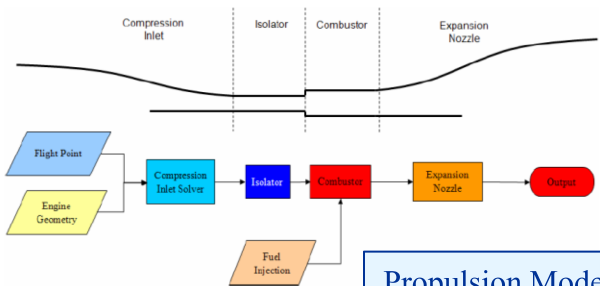
Hydraulics Model



Turbo Jet Engine Model



Dual Mode Scramjet Model

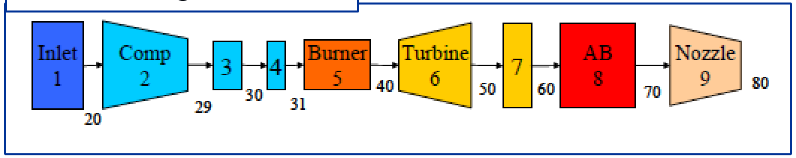


Propulsion Models

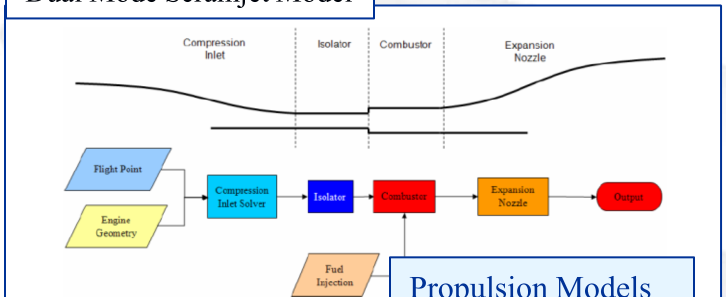
Assume Started Low-Speed and High-Speed Inlets (No external normal shocks)

- Variable Inlet Model (P,T,W)
  - External Compression
    - Inviscid thermally perfect oblique shock theory
  - Supersonic Internal
    - Thermally perfect 1-dimensional steady-state compressible flow
  - Subsonic Internal
    - Unsteady subsonic compression model (control volume)
- Gas Turbine Model
  - Simple 0-dimensional engine model
- Dual Mode Scramjet
  - Isolator
    - Quasi 1-dimensional compressible flow equations
  - Combustor
    - Quasi 1-dimensional combustor model
- Nozzles
  - A simplified, 1-dimensional nozzle model

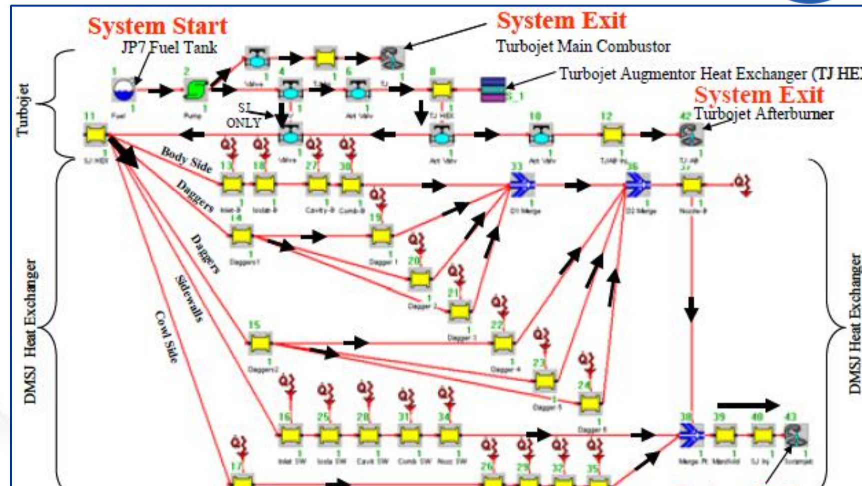
Turbo Jet Engine Model



Dual Mode Scramjet Model



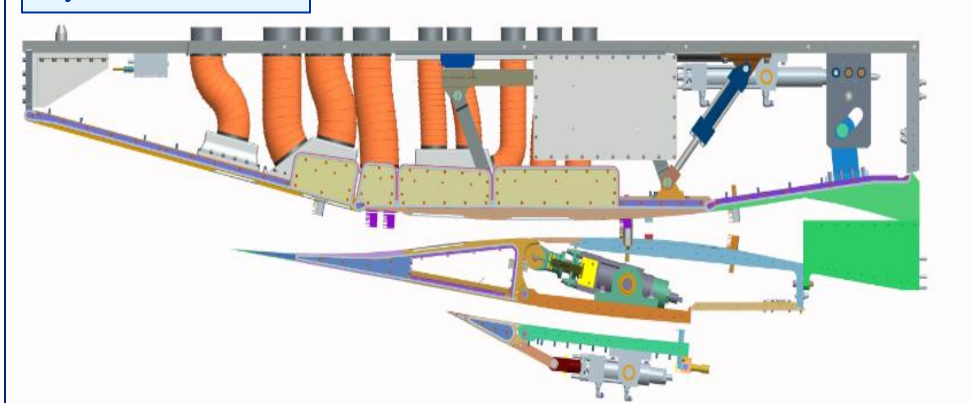
Propulsion Models



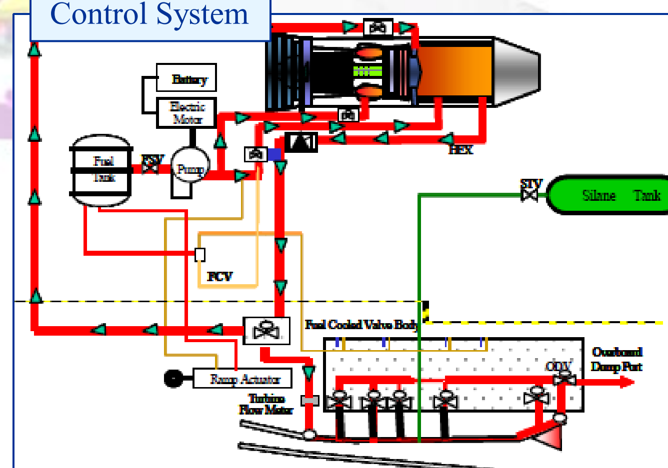
Thermal Management /Fuel System Models

High Mach Transient Engine Cycle Code (HiTECC)

Hydraulics Model

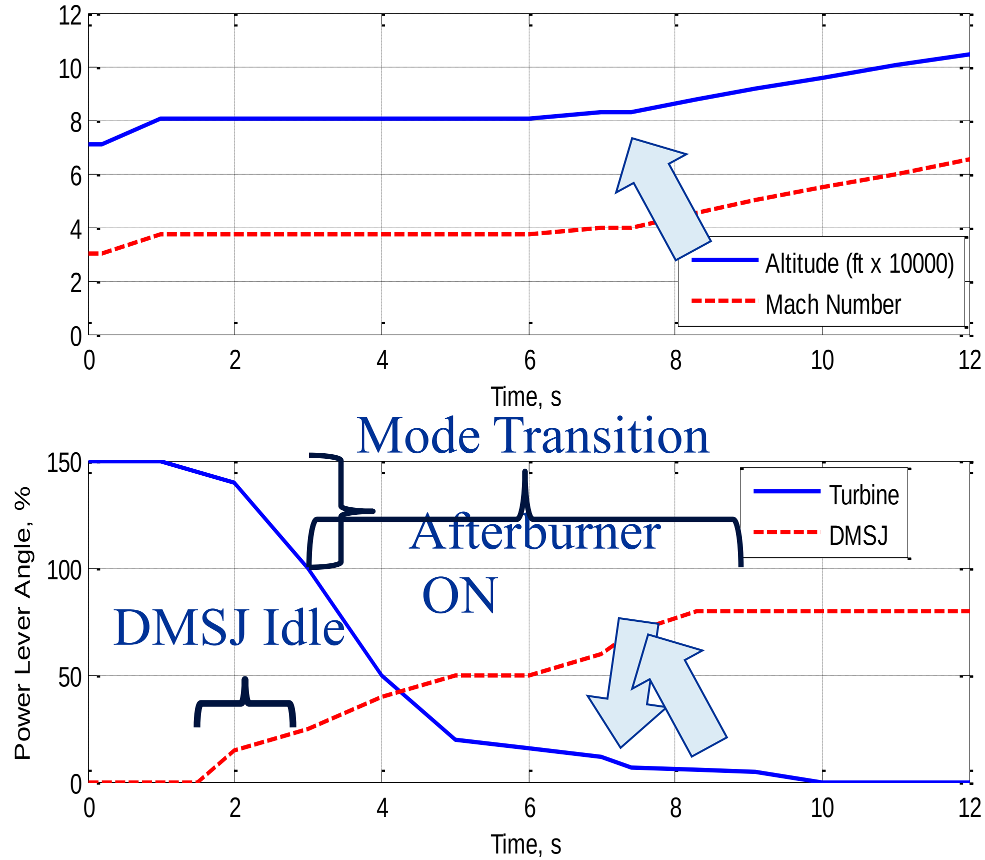


Control System

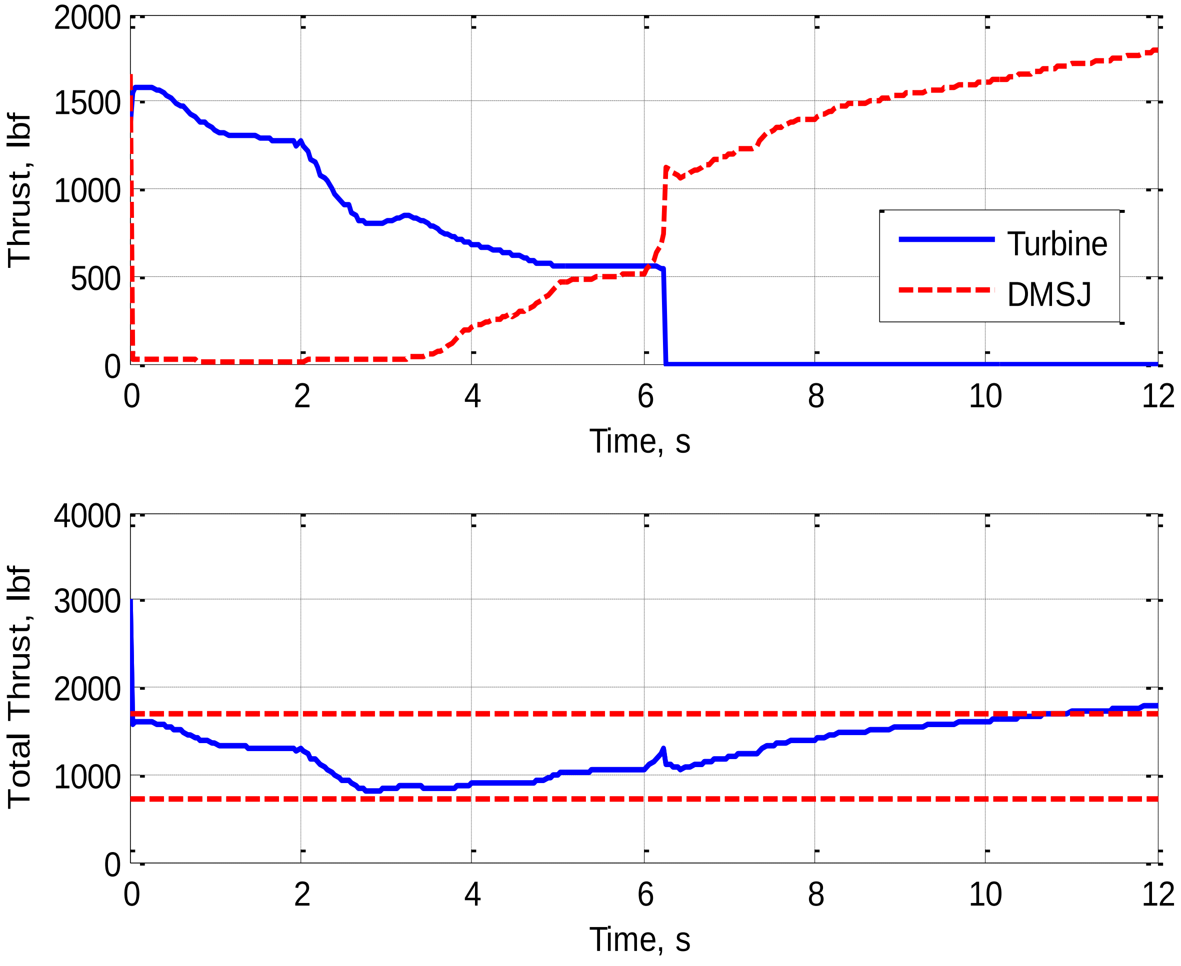


Mode Transition with HiTECC

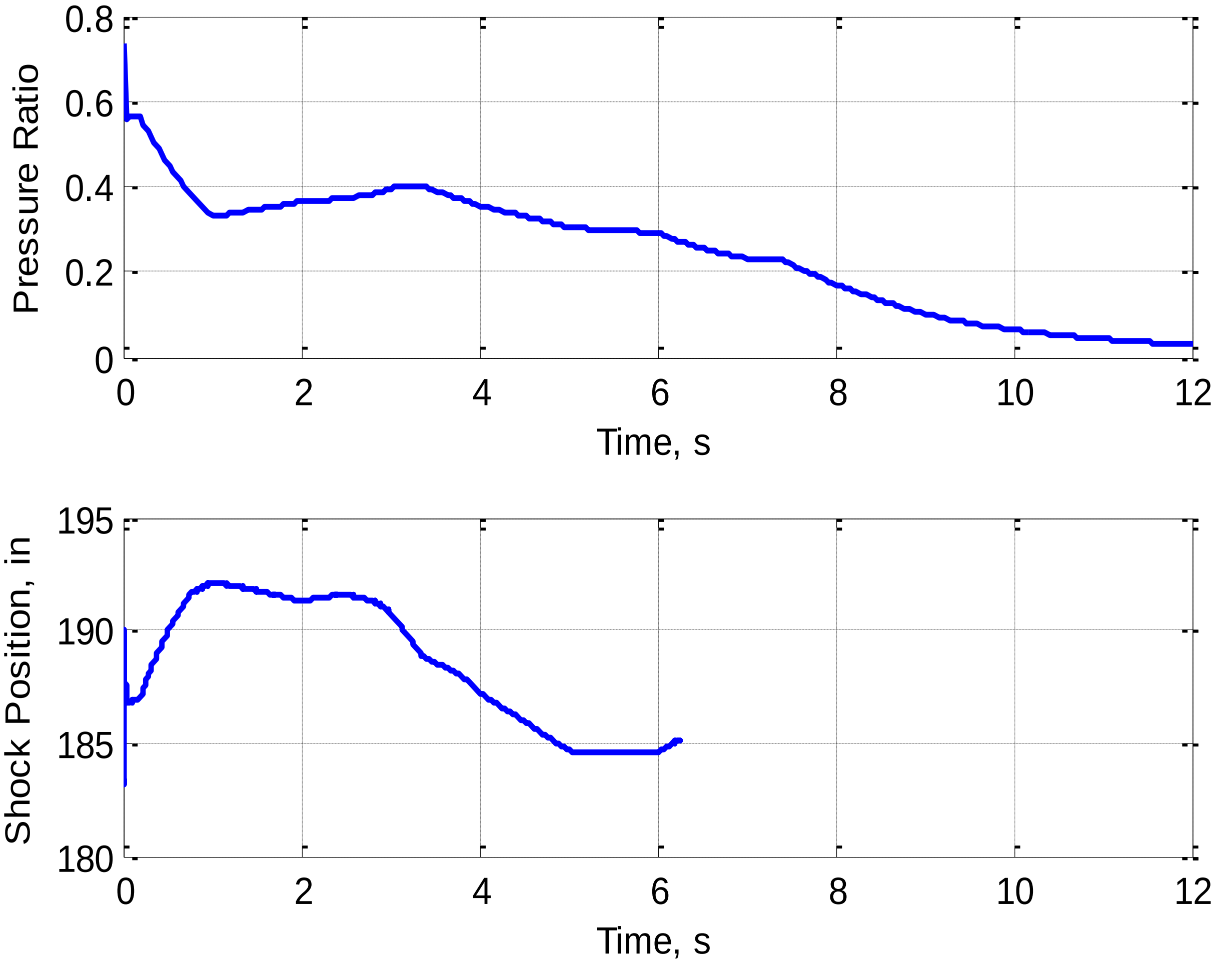
- Mode transition occurs Mach 3.0 -4.0
- Mode transition sequence of events
  - Reach mode transition flight condition (M3.75)
  - Begin afterburner shutdown
  - Start DMSJ
  - Transition power
  - Close off LSFP/ shutdown turbine engine
  - Continue with mission



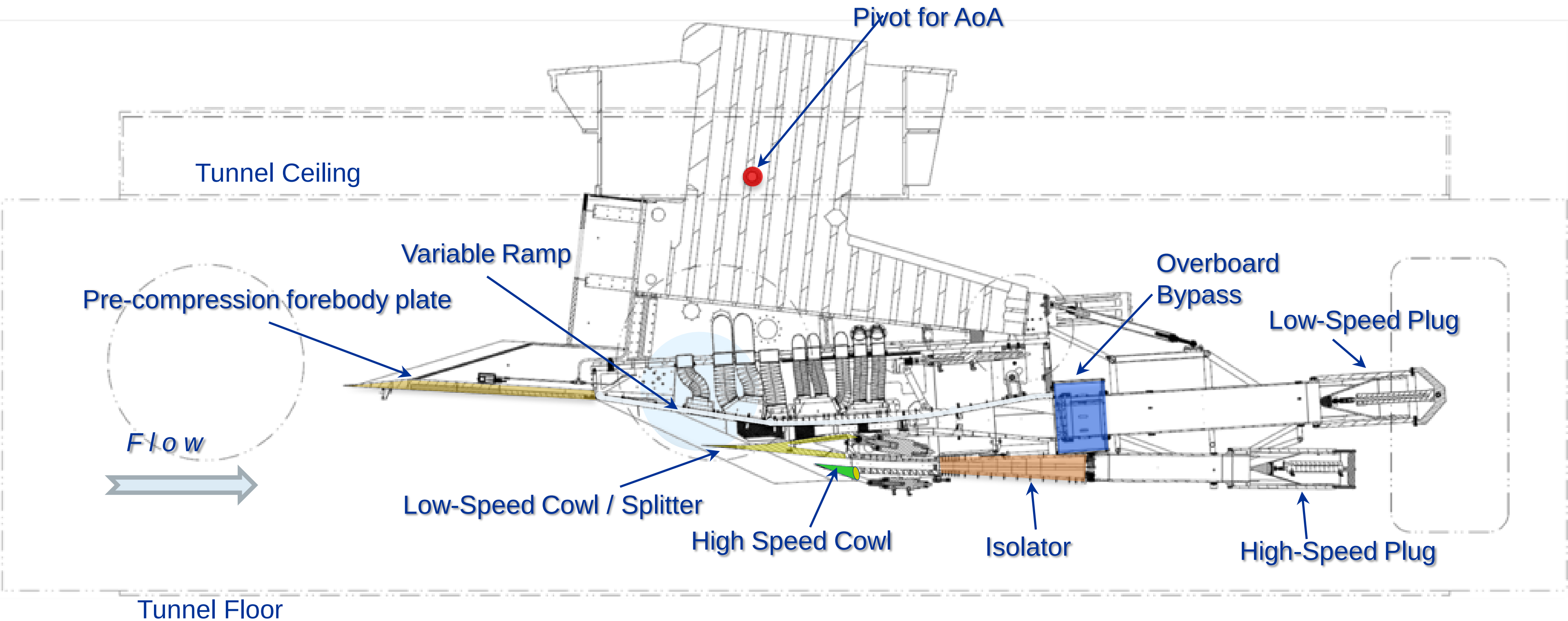
Mode Transition with HiTECC



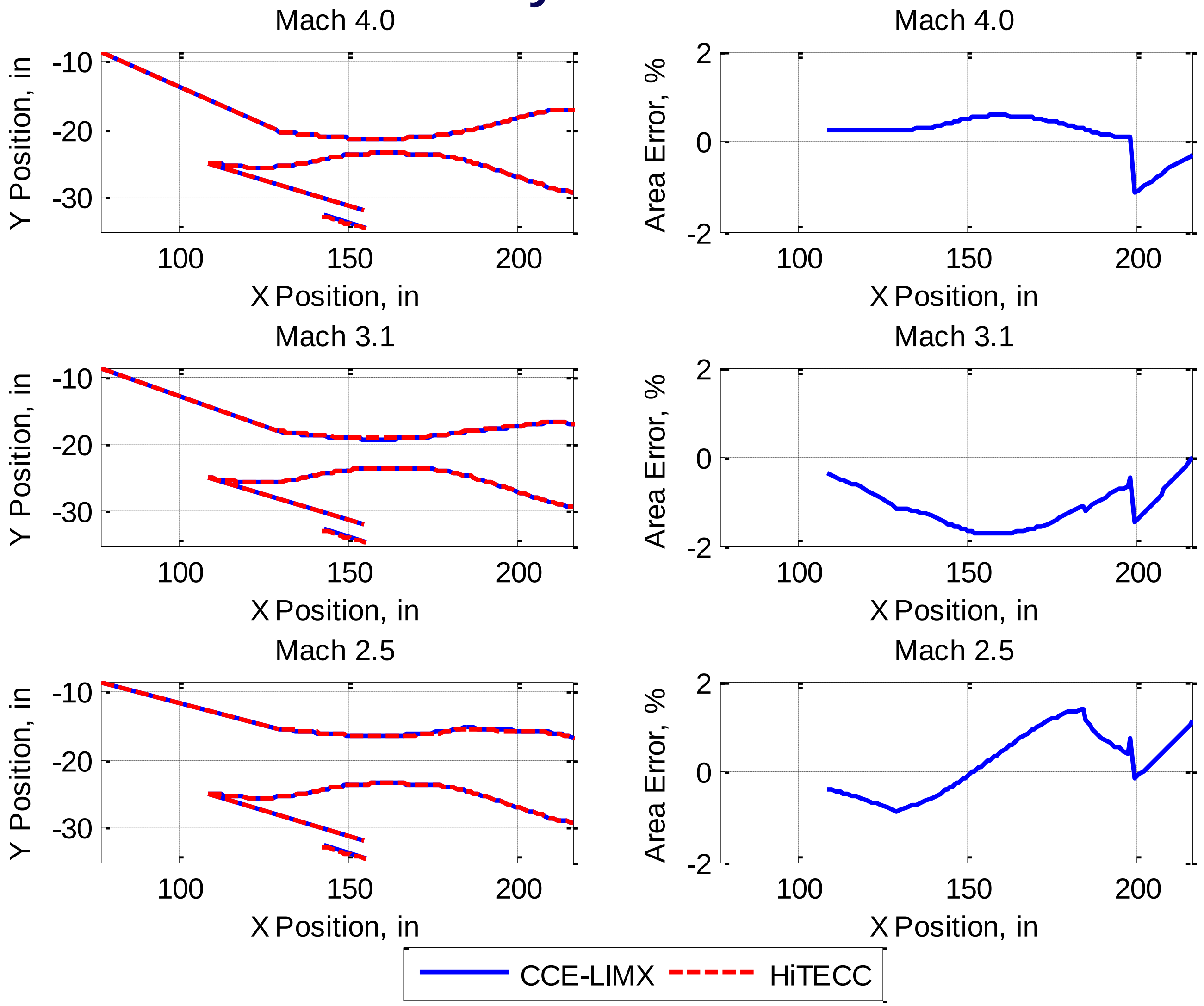
Mode Transition with HiTECC



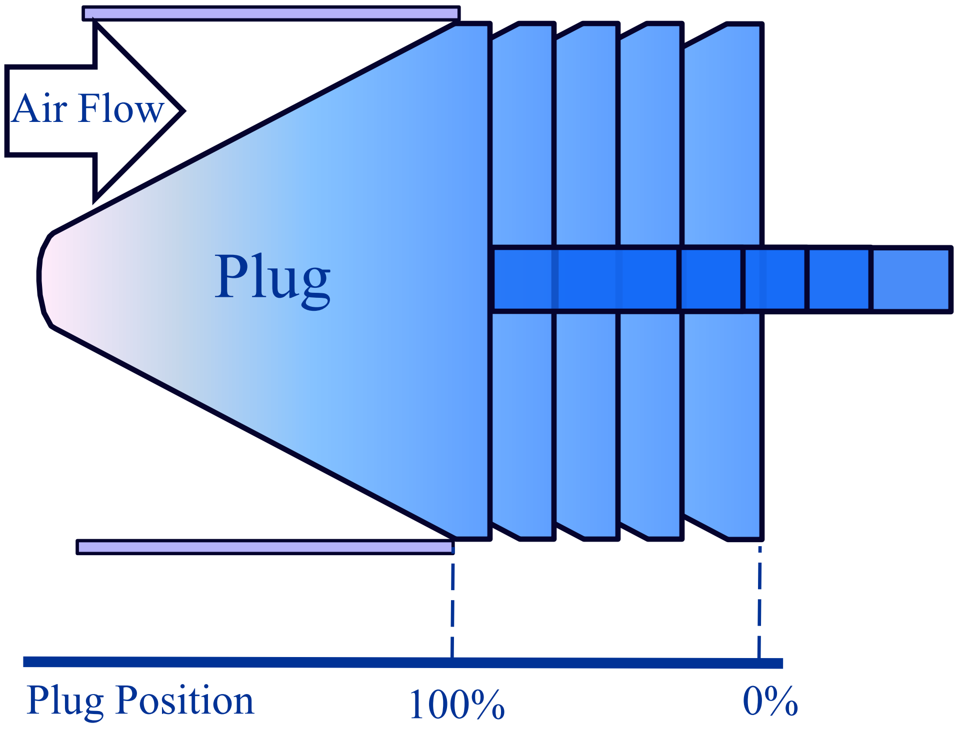
Large-scale Inlet model for Combined Cycle Engine Mode Transition Studies (CCE-LIMX)

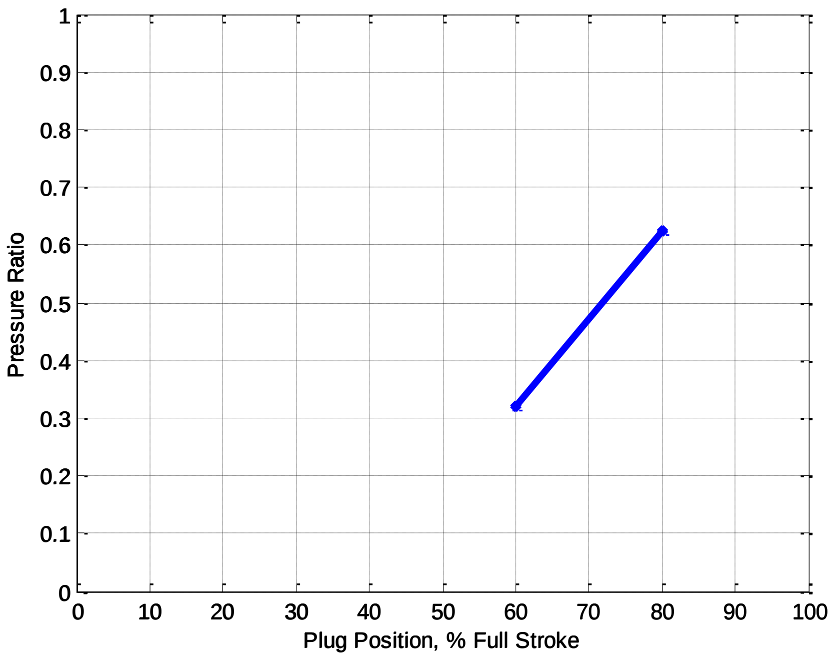


Redesign Geometry, Actuators, and Control Systems

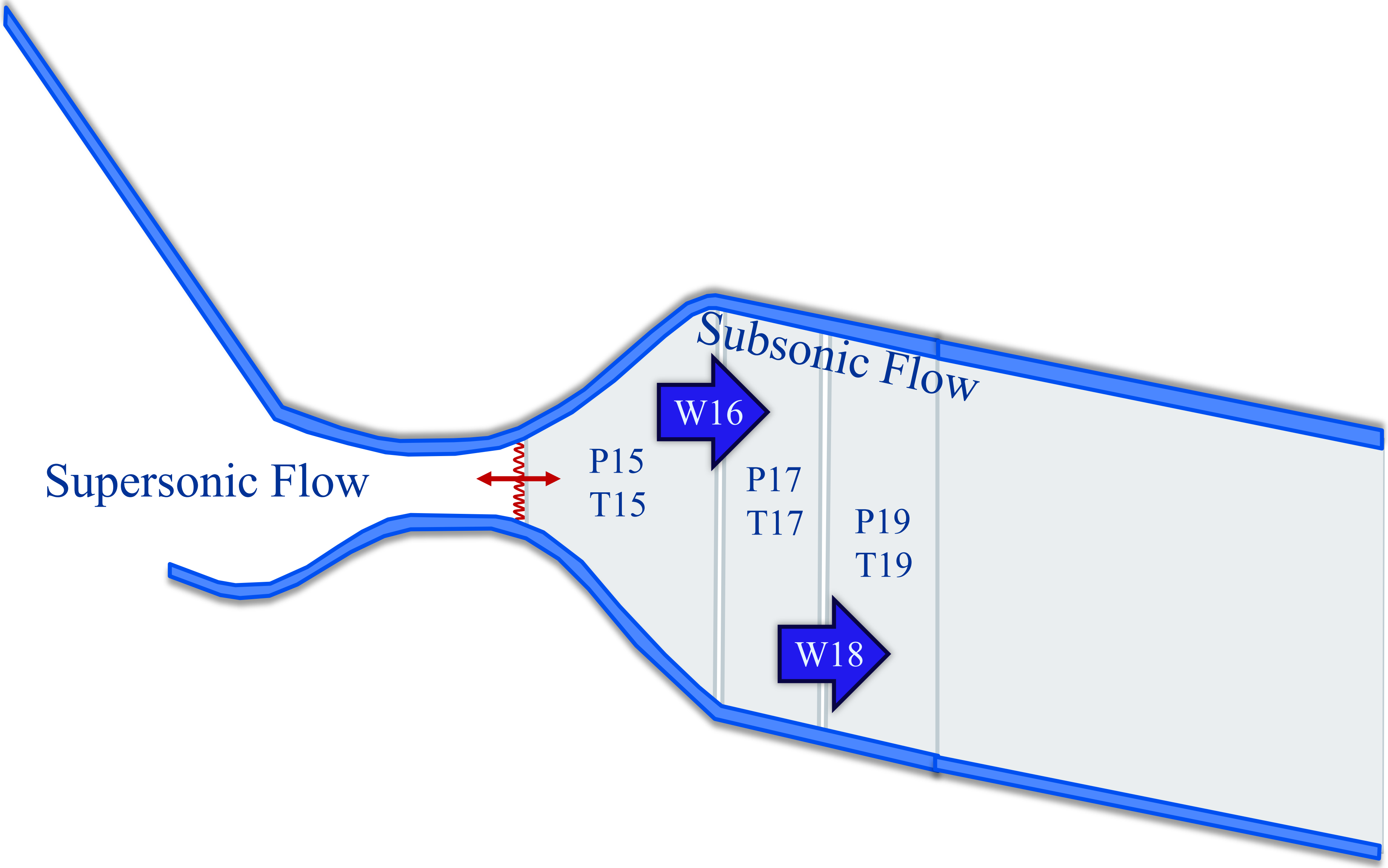


Replacement of Turbine Engines with a Plug

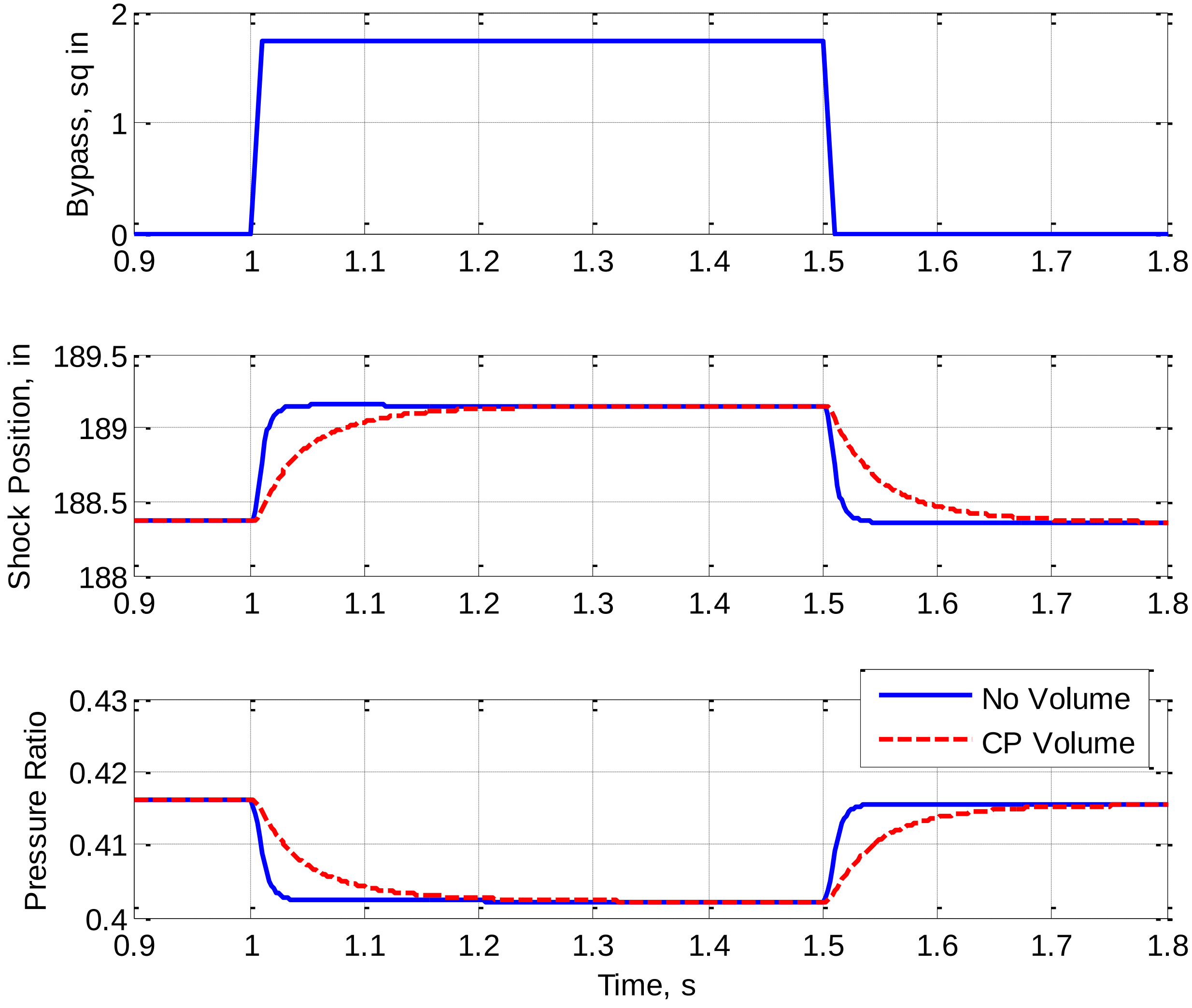




Addition of the Cold Pipe Volume

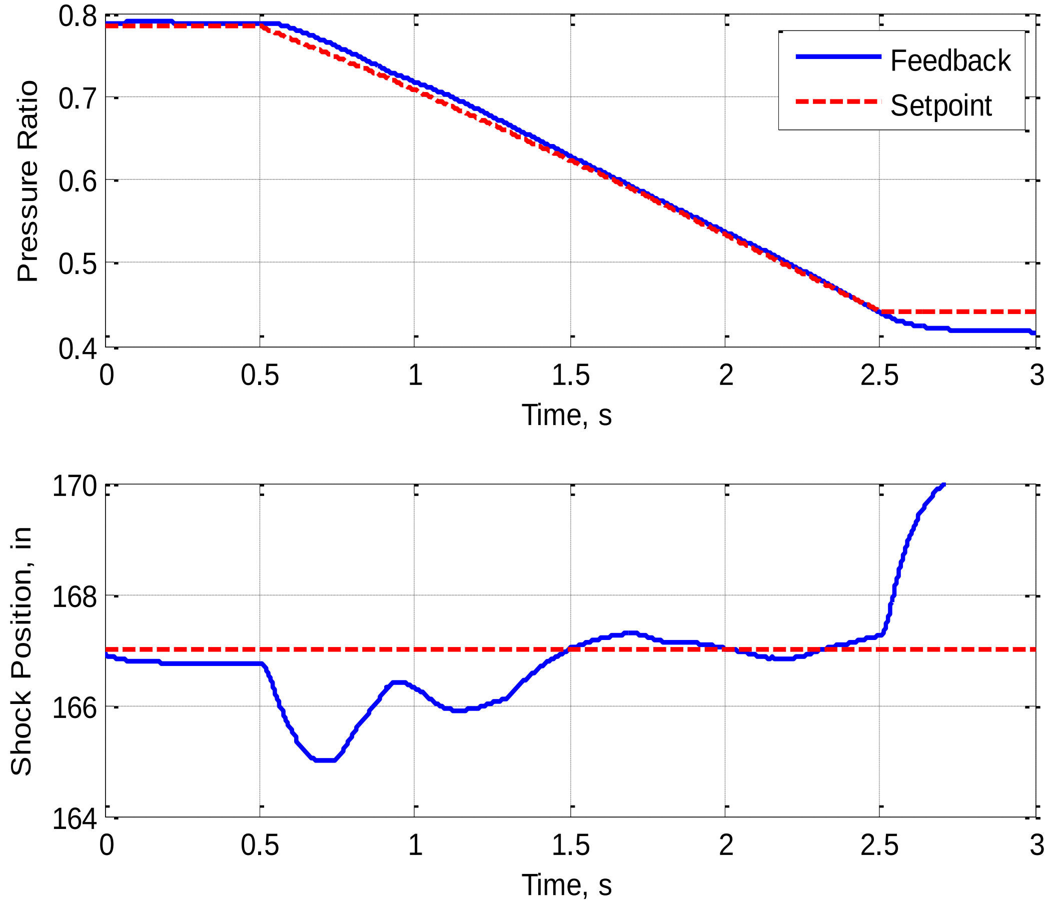


Dynamic Response with Additional Volume



Mode Transition with the CCE-LIMX

- Pressure ratio setpoint is dependent on the splitter angle
- System is driven to starting pressure ratio by the plug



Future Work with HiTECC

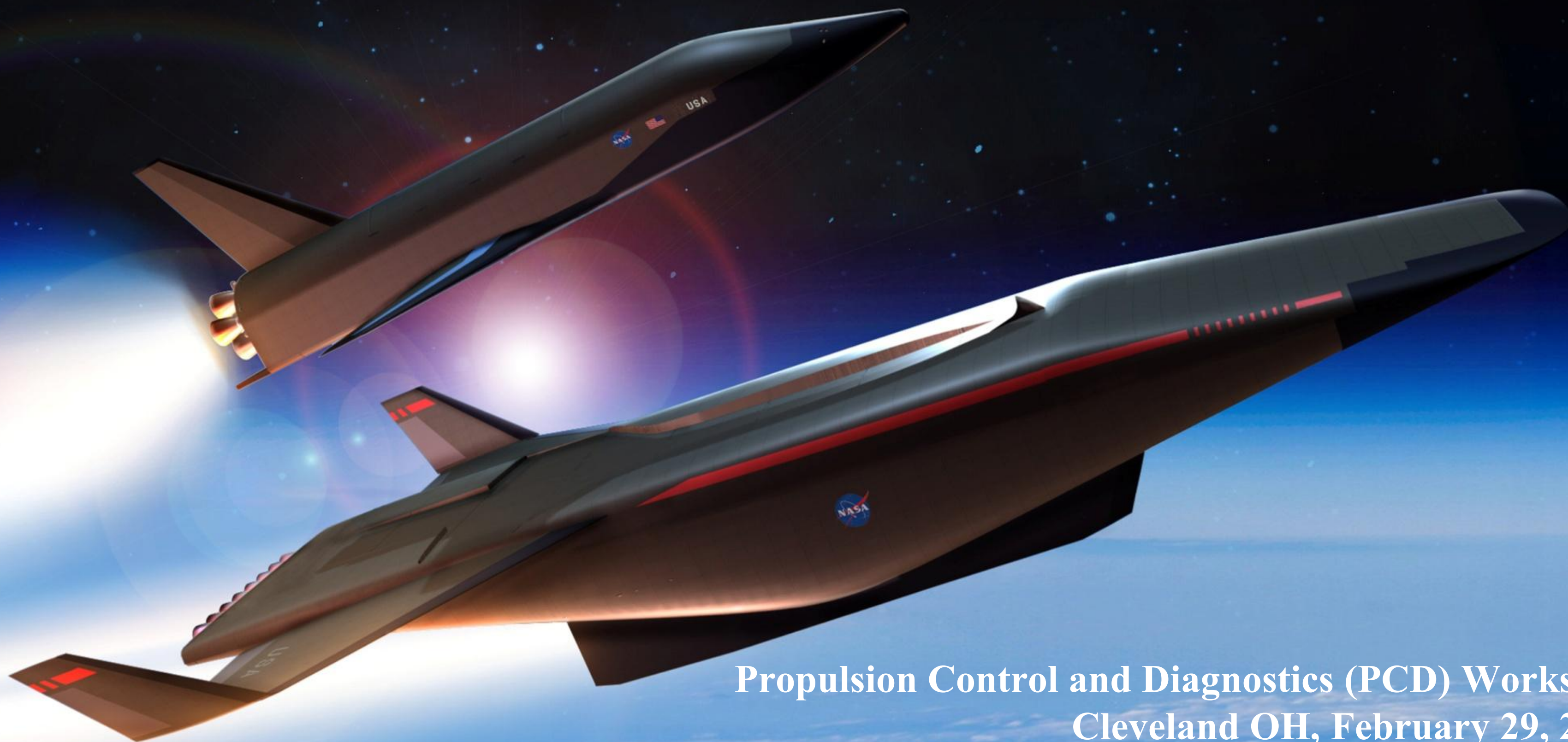
- Develop linear models for diffuser (subsonic).
- Compare experimental data with HiTECC.
- Use HiTECC to develop and test candidate mode transition control algorithms before implementation.

CCE Inlet Wind Tunnel Experiments

Combined Cycle Engine (CCE) Mode Transition

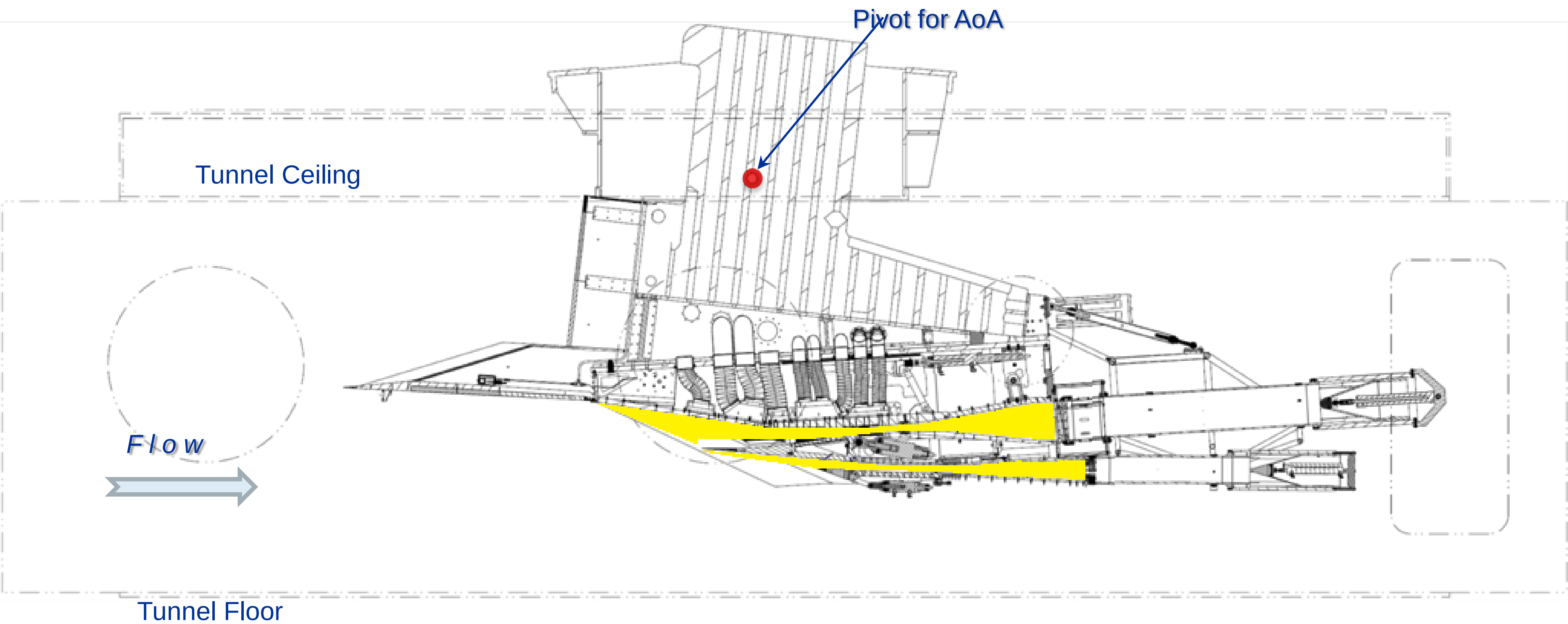
Fundamental Aeronautics – Hypersonic Project

Thomas J. Stueber
NASA Glenn Research Center
Cleveland, Ohio

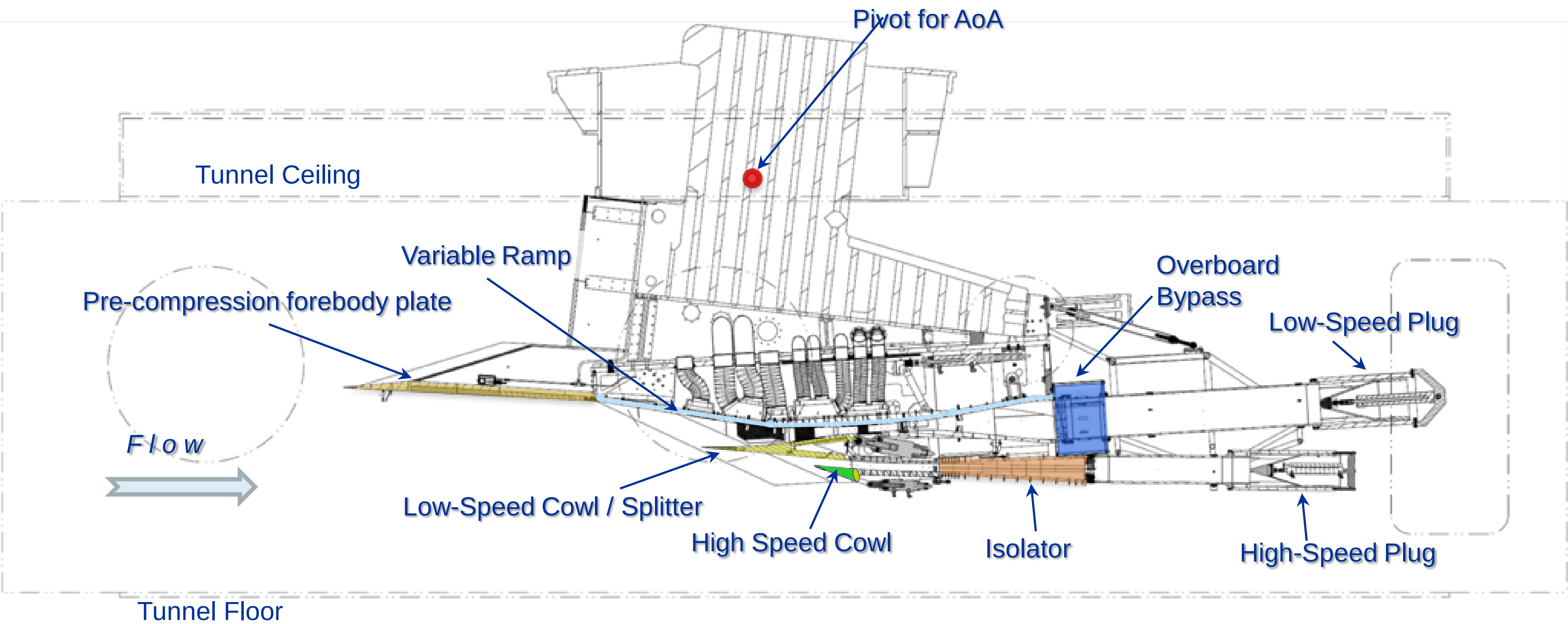


Propulsion Control and Diagnostics (PCD) Workshop
Cleveland OH, February 29, 2012

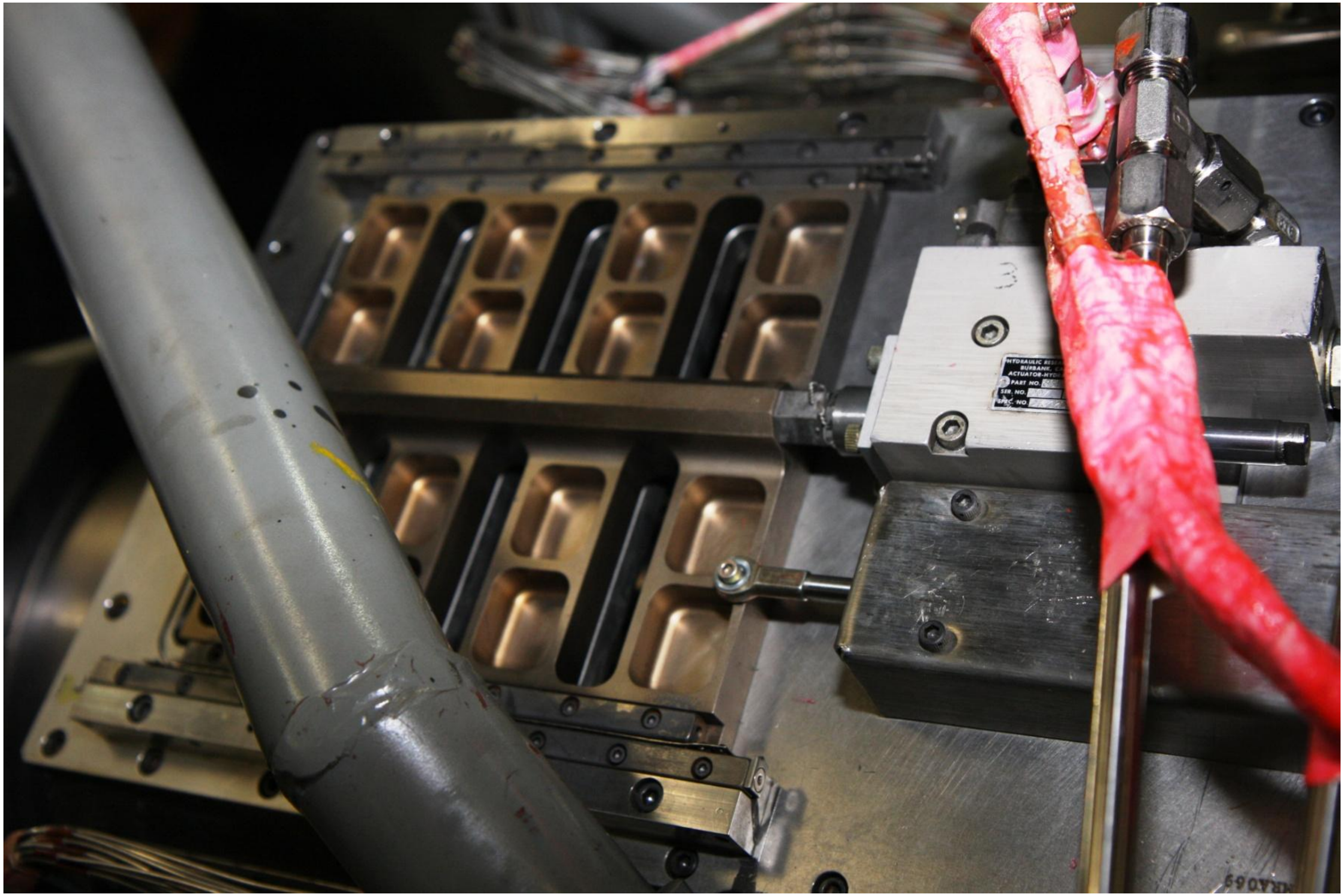
CCE-LIMX Model Features



CCE-LIMX Model Features



One of Four Bypass Doors



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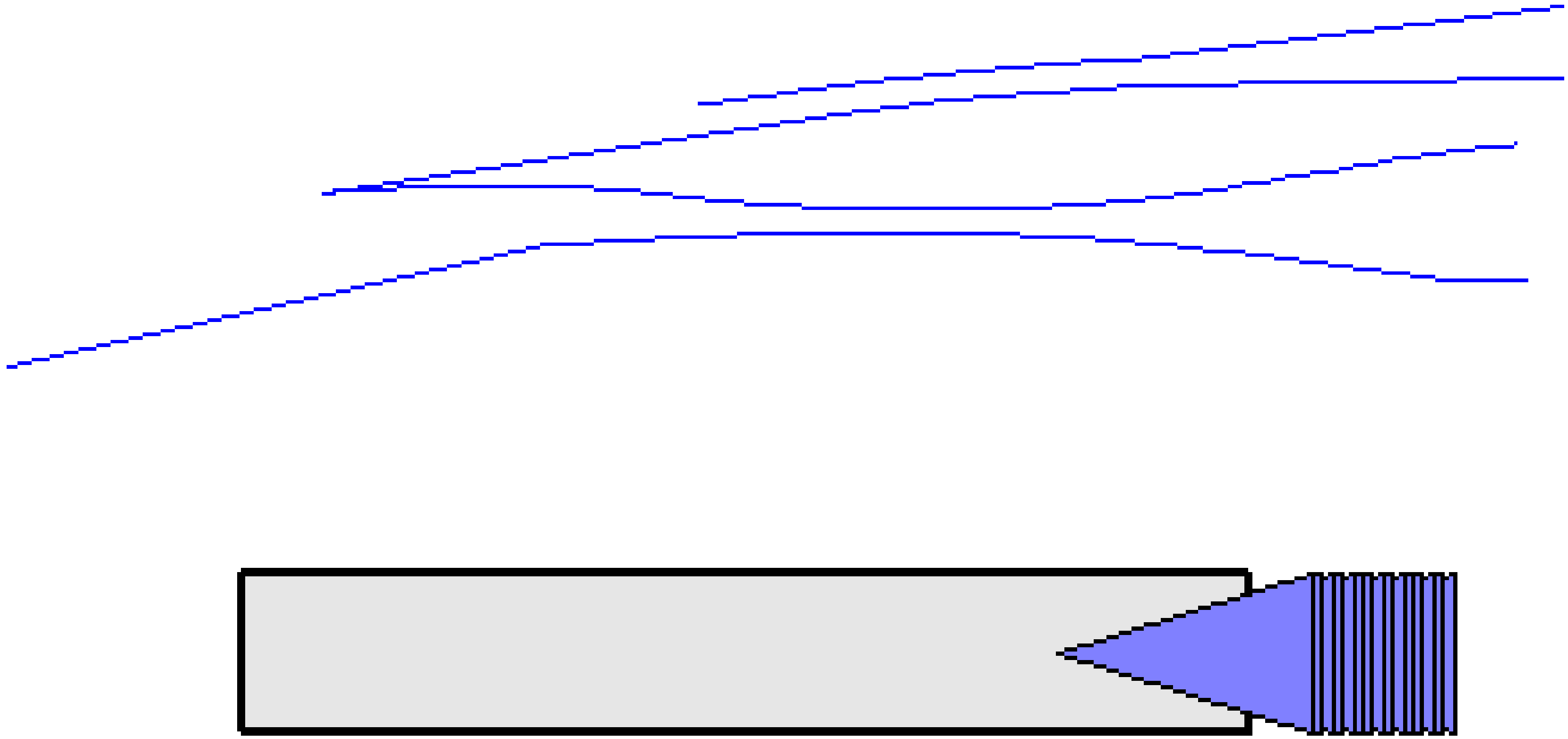
Phase 1: Inlet Characterization and Performance Testing



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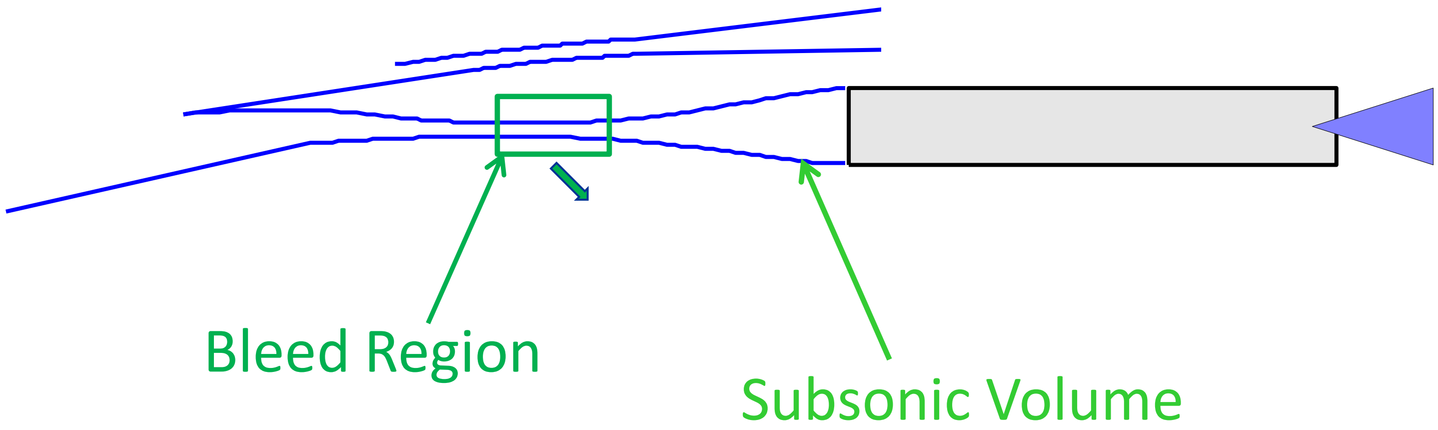
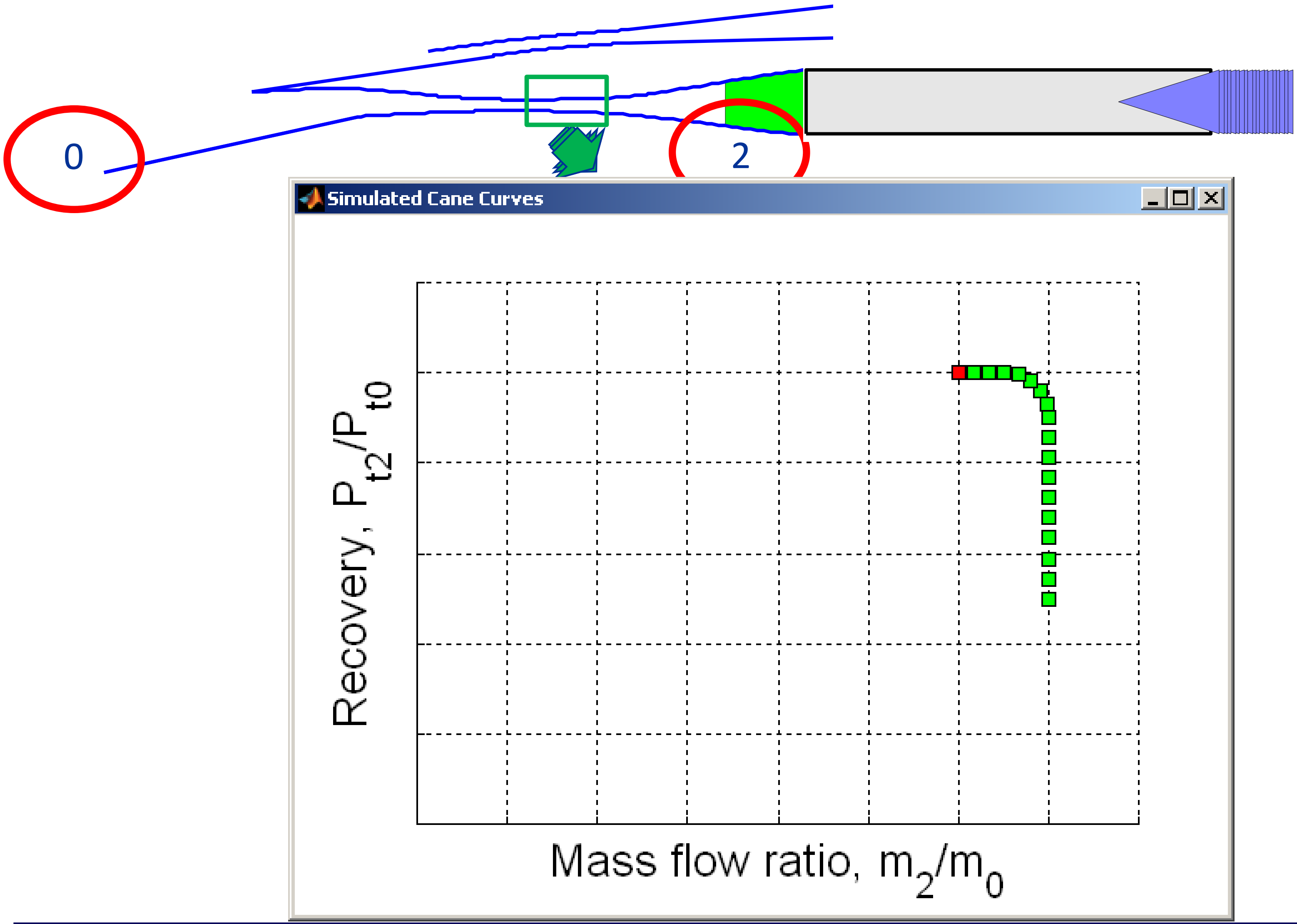


Phase I: Inlet Characterization and Performance Testing



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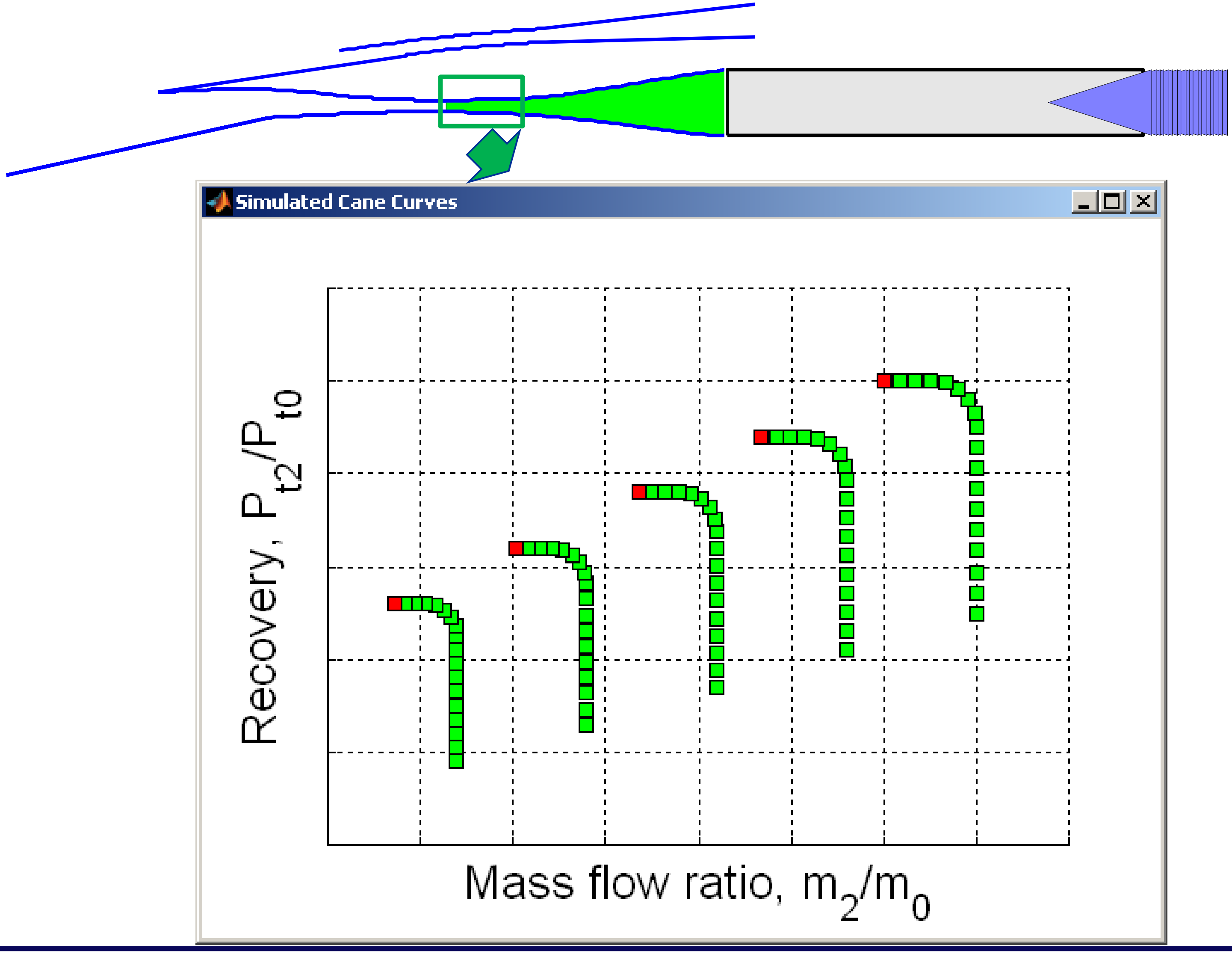

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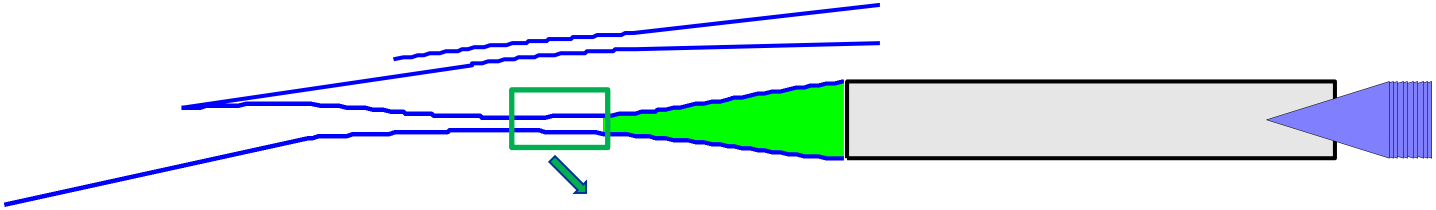
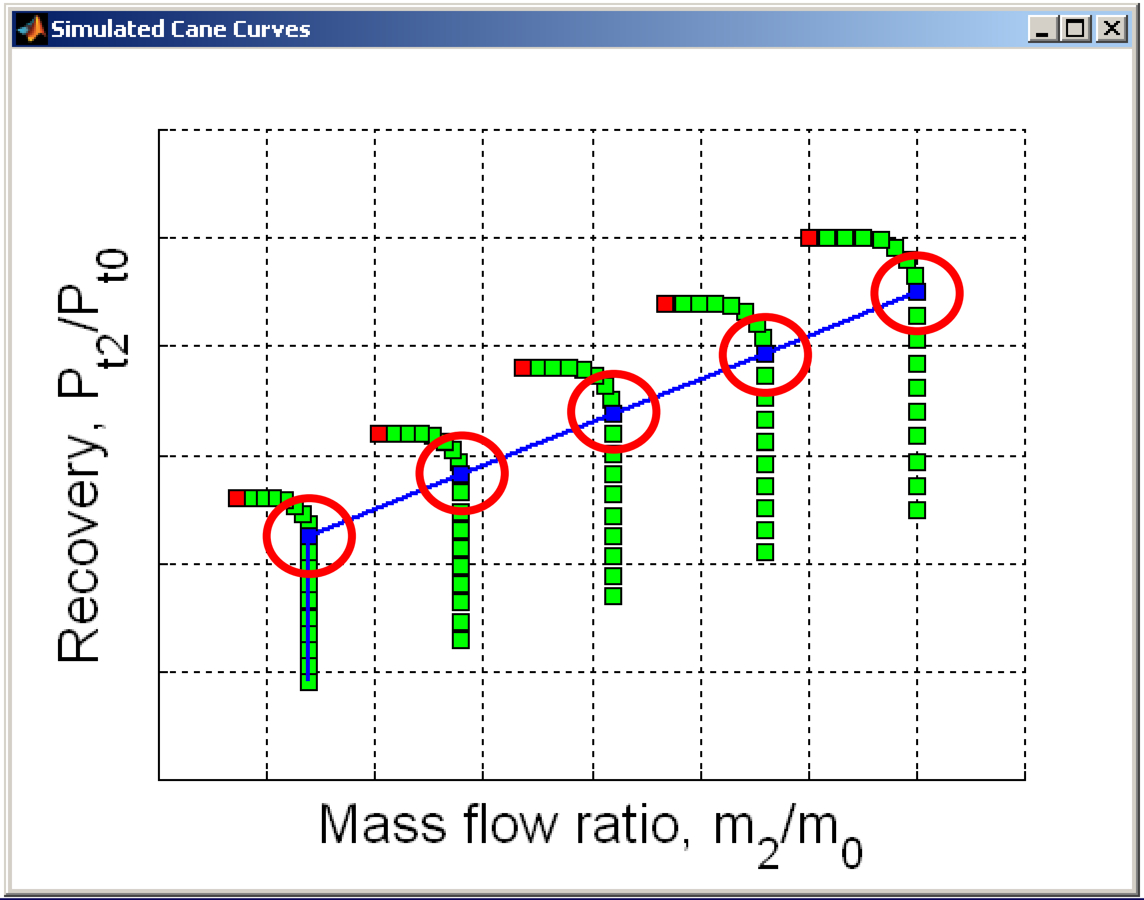
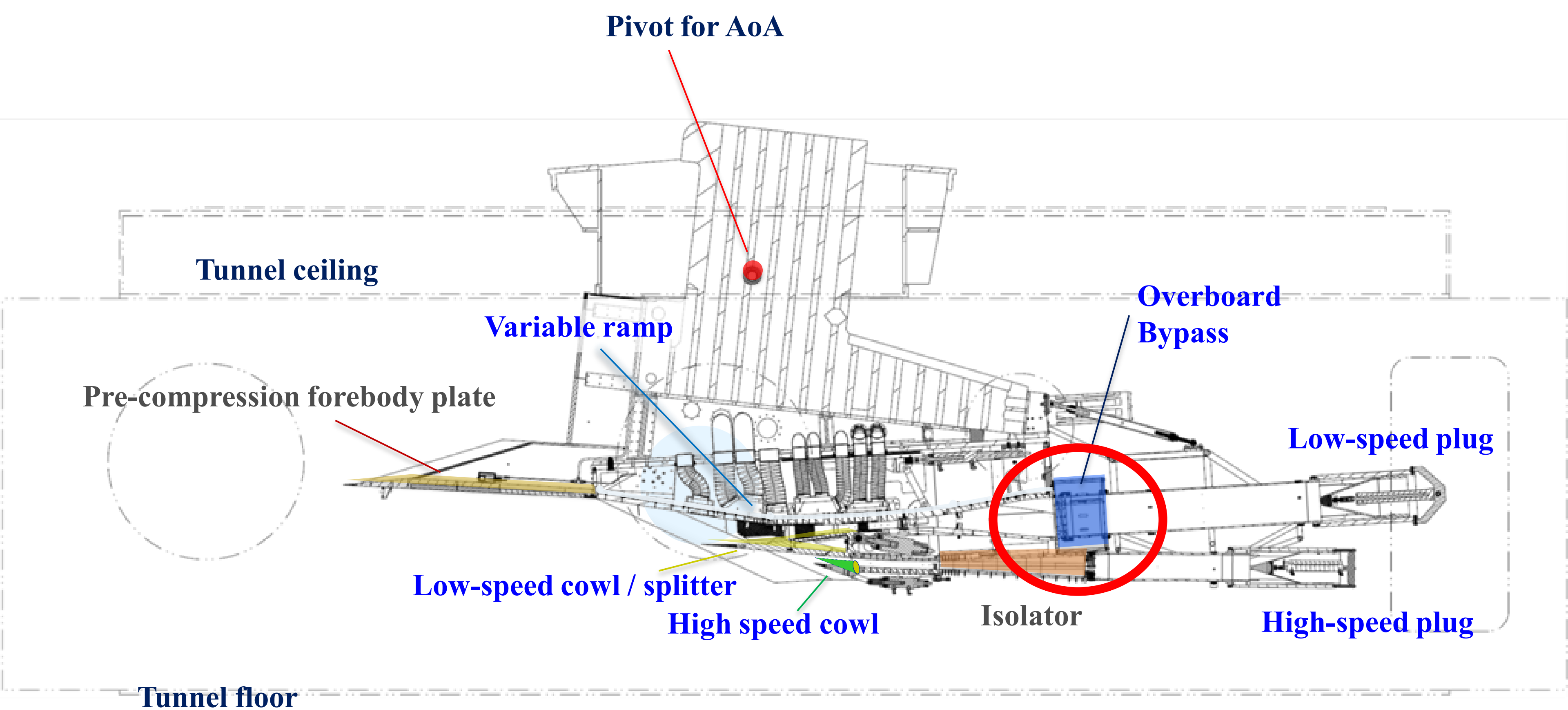


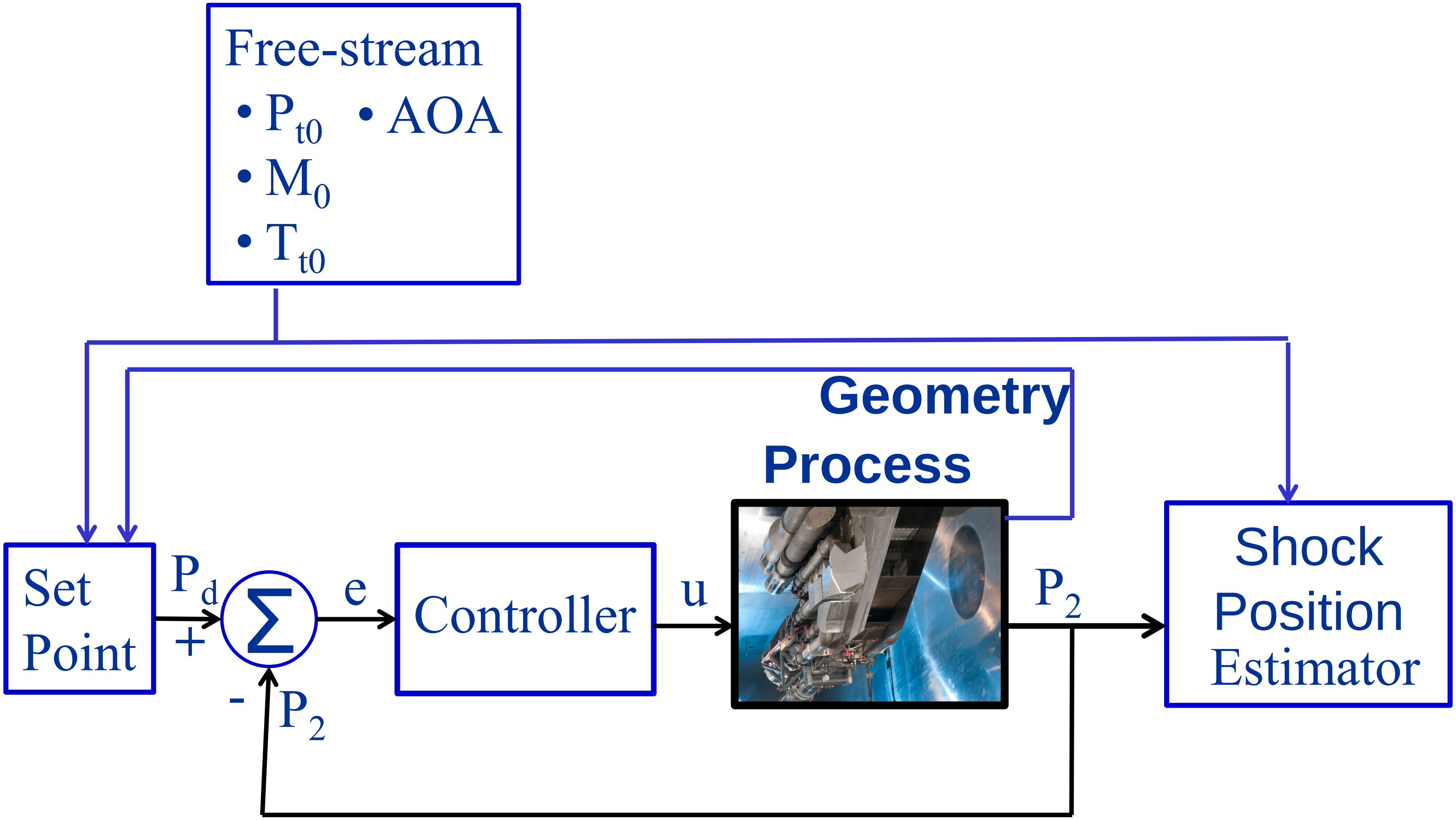


Controlling The CCE-LIMX

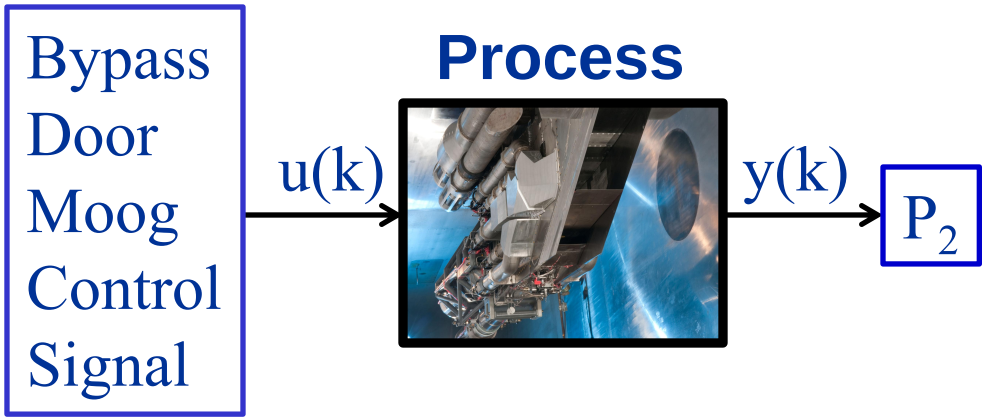


Design a Controller

Design a Controller



First, Design the Model



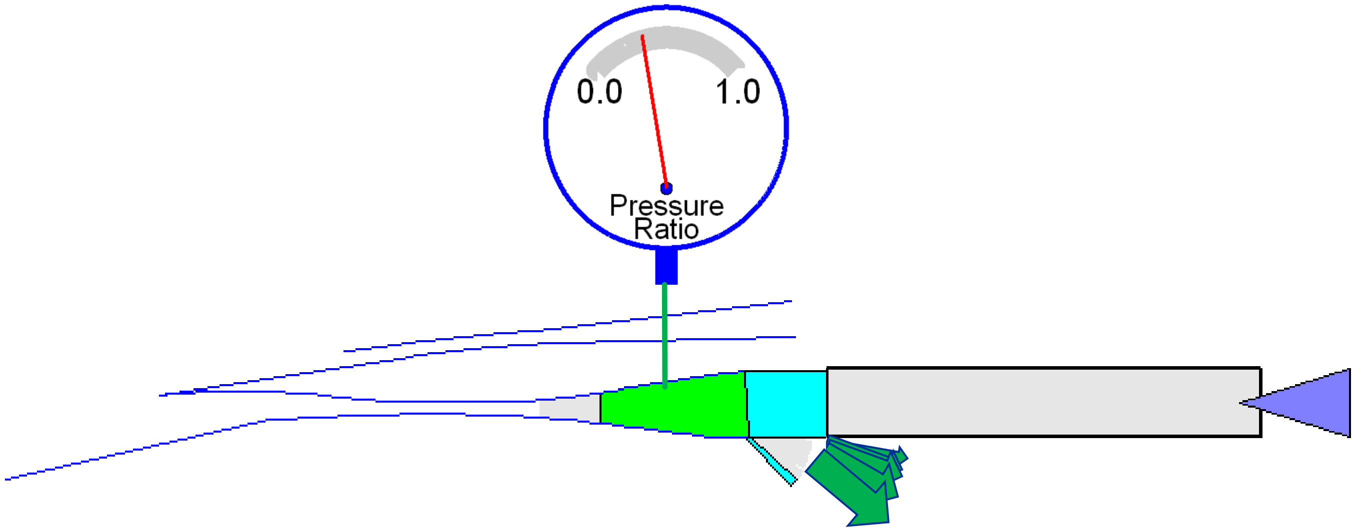
Process assumptions:

Sufficient control design simulation can be captured in a linear computational autoregressive control model.

Autoregressive model:

$$y(k+1) = a_0 y(k) + a_1 y(k-1) + \ldots + a_n y(k-n) + b_0 u(k) + b_1 u(k-1) + \ldots + b_n u(k-n)$$

Stimulate the Process



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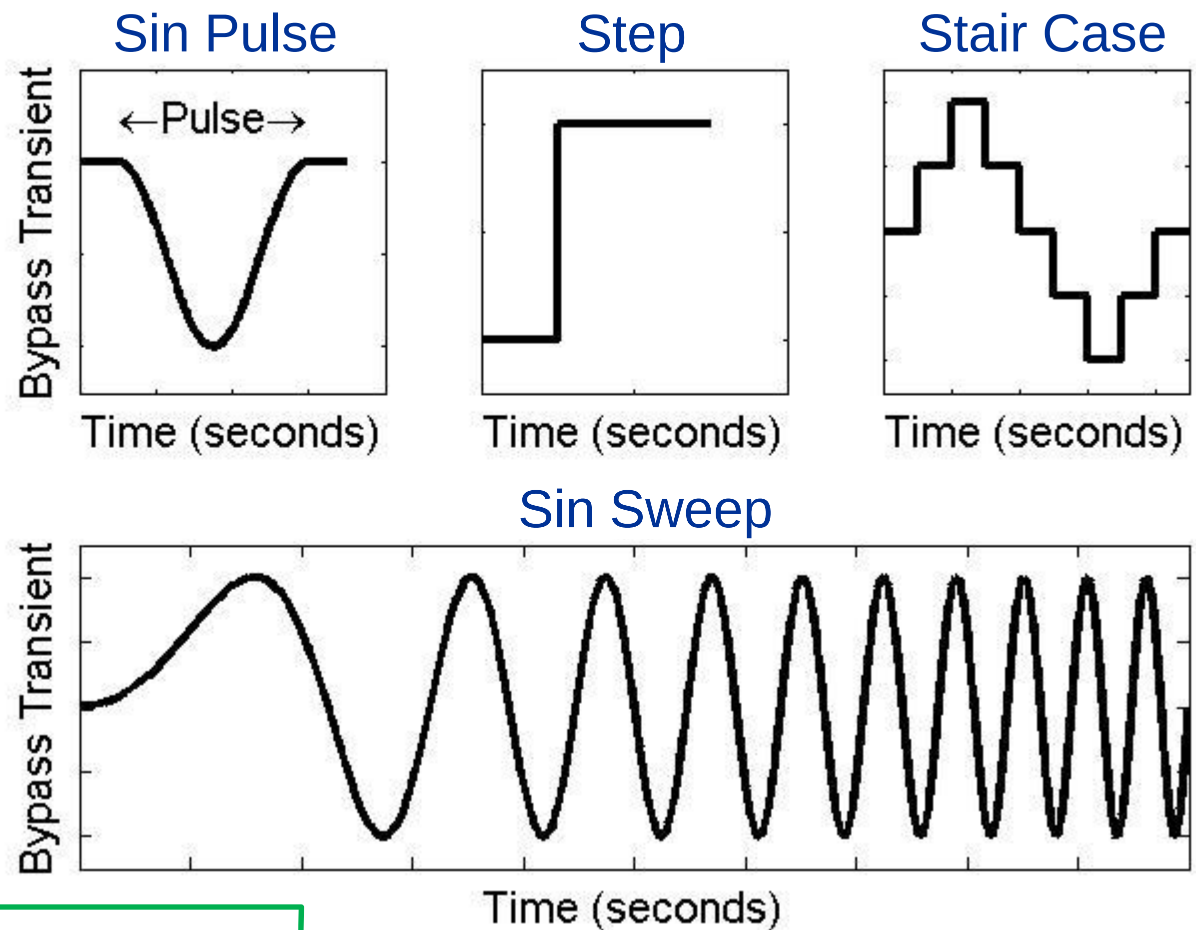

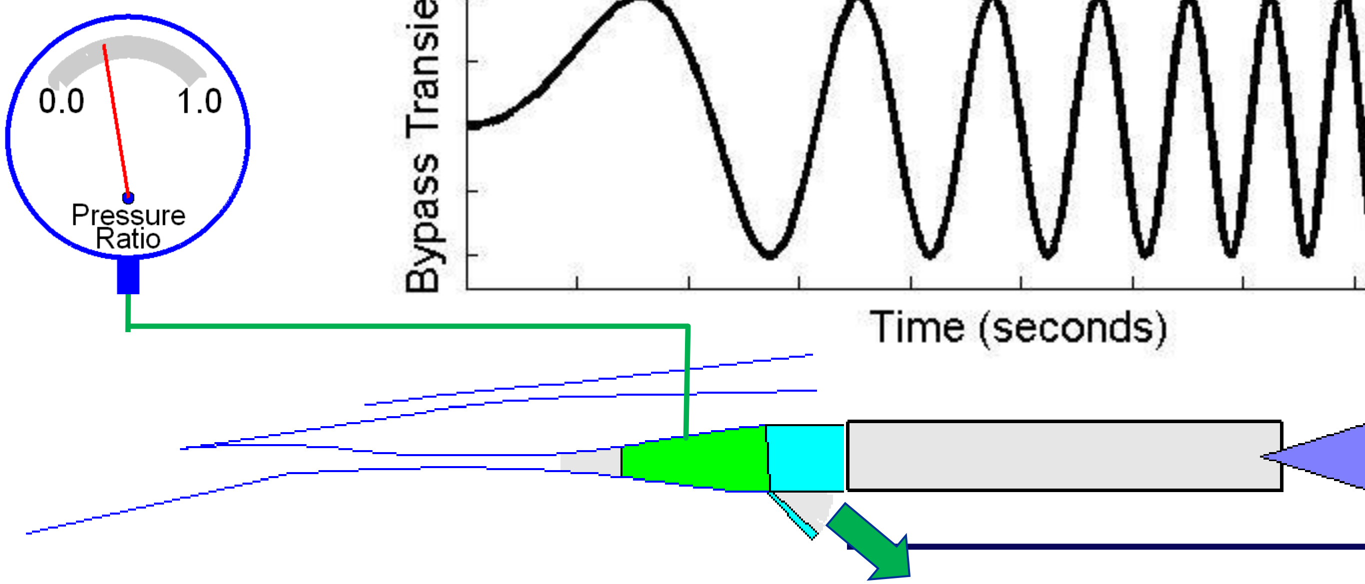

GNC Phase 2 Accomplishments

- Experiment data is ITAR restricted
- Test matrix status Phase 2 Mach 4
  - 642 Experiments identified, ~89 hrs
    - Main (LST1 and HST1) schedule—506 experiments, ~49 hrs
    - First alternate (LST1 and HST2) schedule—68 experiments, ~20 hrs
    - Second alternate (LST2 and HST2) schedule—68 experiments, ~20 hrs
  - Reduced Matix—393 Experiments selected, ~29 hrs
    - Main schedule—378 experiments completed, 38.25 hrs
    - Alternates—0 experiments completed
  - Experiments:
    - Step, Sinusoidal Sweep, Sustained, Sinusoid
    - Staircase, Transient Stability Index (Tsi),
    - Unstart, Buzz, Restart
- Test window: 8/29/2011 – 10/19/2011
- 11 run nights (data collection)

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International Traffic in Arms Regulation

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High-Speed flow path Track-2

Low-Speed flow path Track-1

SysID Rack Performance

- Calibrations in parallel with 10- x 10-foot facility calibration operations.
- Control transfer from facility to SysID Rack and back
  - Small changes in actuator positions due to discrepancy in interpreted actuator positions—insignificant.
    - We had exposure to feedback signals in EU,
    - Better to match voltage signals applied to the controller.
  - Verified SysID Rack controllability prior to facility pump down
  - Verified SysID Rack data acquisition performance while facility pump down.
- Data acquisition and experiment control performed flawlessly

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GRC 10- x 10-foot SWT

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SysID Rack Performance

- Host Laptop II choked on data transfer to host from target—about 4 events
  - Control transfer back to facility
  - Reboot SysID Rack (about 25 min turn around).
  - Enabled a few Phase I type experiments during down time
  - Issue resolved by replacing Host II with Host I.
- Data saved in multiple locations
- Data reduction computer and tools worked flawlessly

Hypersonic TBCC Controls Team
Future Paths

- Continue CCE Phase 2 testing
- Reduce Phase 2 data to control design models (CDMs)
- Compare physics based computational models against CDMs.
- Design control algorithm for maintaining desired pressure recovery
- CCE-LIMX Phase 3 and 4 testing (if funding becomes available)
  - Test controller on physics based computational models
  - Buildup SysID Rack to support Phase 3 experiments
- Investigate control applications for dual-mode scramjet engine flow paths.

Summary

- Well underway to meeting Phase 1 and 2 objectives:
  - Completed:
    - A control system, hardware and software, was designed to demonstrate inlet mode transition.
    - System identification experiments were designed to study the dynamic issues associated with inlet mode transition.
    - A control system was designed, hardware and software, to conduct the system identification experiments and record the experiment data.
    - System identification experiments at Mach 4 mode transition operating points.
  - Underway
    - Dynamic analysis of the system identification experiment data
      - frequency spectrum of interest for active control
      - Experiment based control design model (CDM) development
    - Preparing physics based models to simulate dynamics of inlet mode transition (validation).

Summary

- Well underway to meeting Phase 1 and 2 objectives:
  - Underway (continued):
    - Designing controllers based on:
      - experimental data
      - physics based computational models.
    - Testing controller algorithms on physics based computational models.

End of CCE Wind Tunnel Experiments

Discussion Guideline

Topic:

• Are we working on the right controls/diagnostics technologies w.r.t. project objectives?

• Do we have the right approach?

• Are we appropriately disseminating information on our efforts and the progress being made?

• Are there any other efforts ongoing that we can leverage?